The Role of the Polar Vortex in Atmosphere-Ionosphere Coupling

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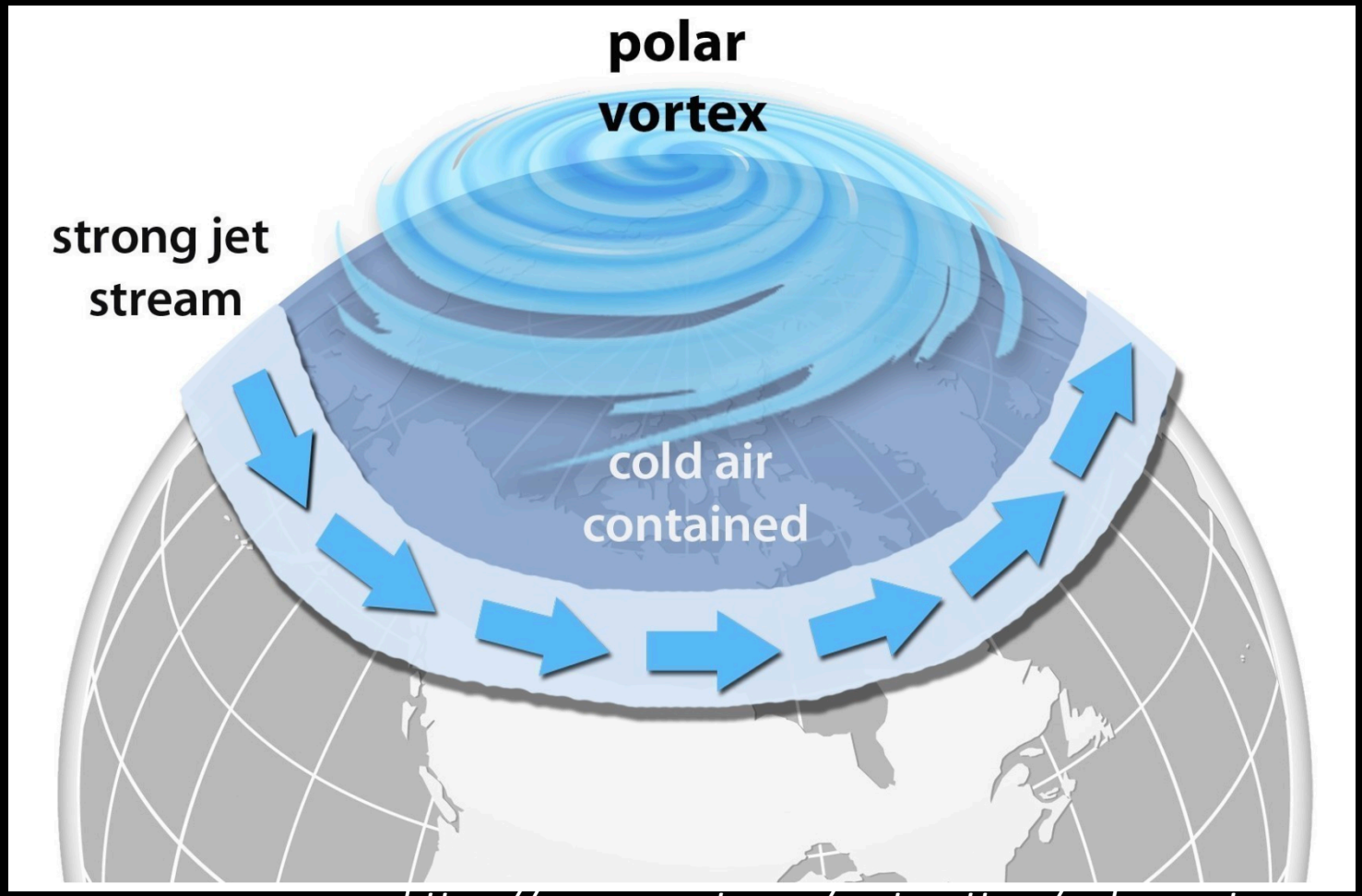
Outline

- Introduction
  - The stratospheric & mesospheric polar vortex
  - Planetary Waves (PWs), Tides, Gravity Waves (GWs)
  - Sudden Stratospheric Warmings
- Bottom-Up Coupling via PWs
  - Winds, PWs, Tides
- Bottom-Up Coupling via GWs
  - MSTIDs
- Predictability

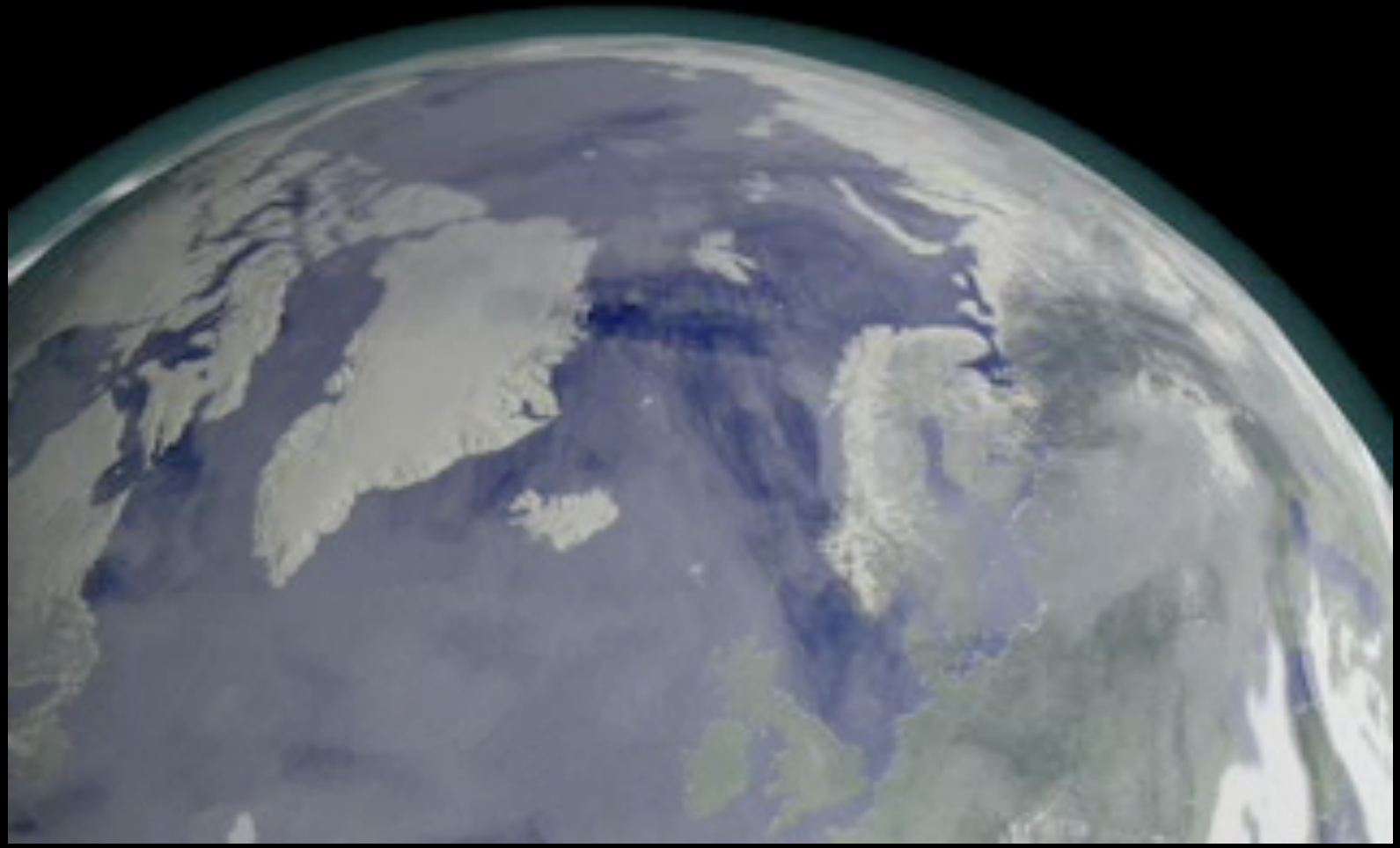
The winter polar vortex on Earth



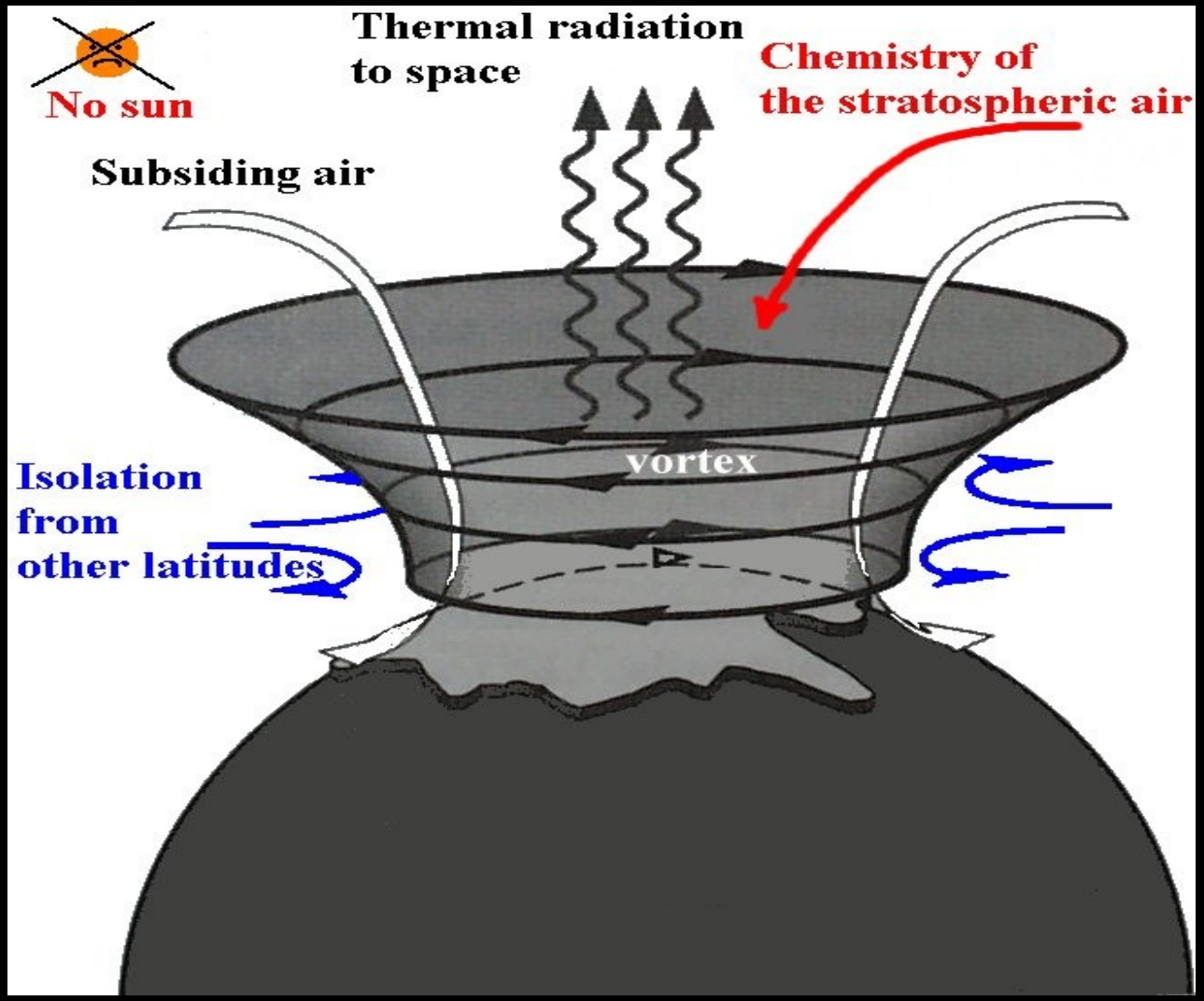
https://www.rmets.org/metmatters/polar-vortex-ssw

- During winter in the dark polar night there is UV to for O_3 to absorb
- This results in a very cold polar stratosphere
- A west-to-east jet stream encircles the cold air

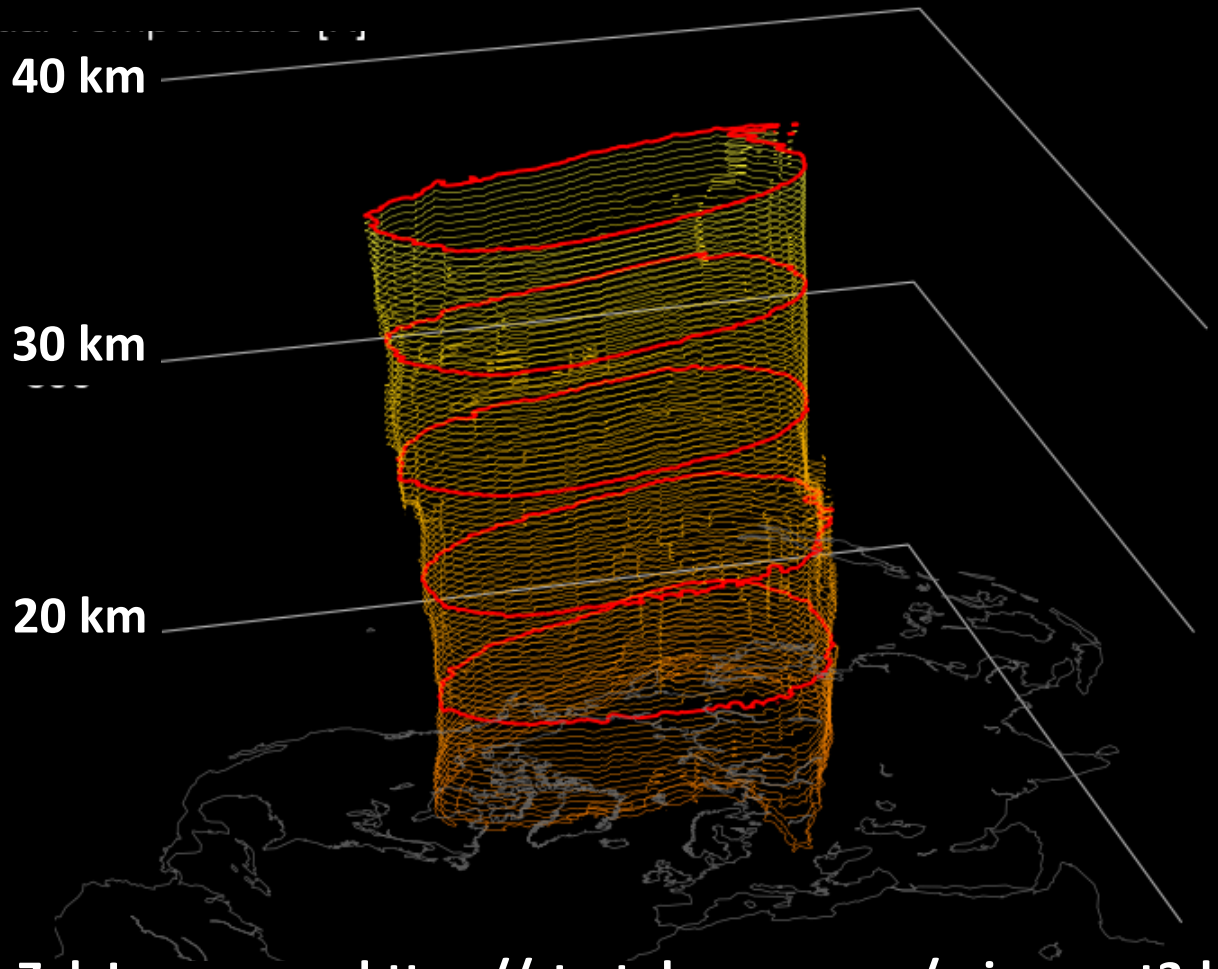
The Arctic polar vortex wobbles about the pole from day to day due to weather below



The Antarctic Vortex

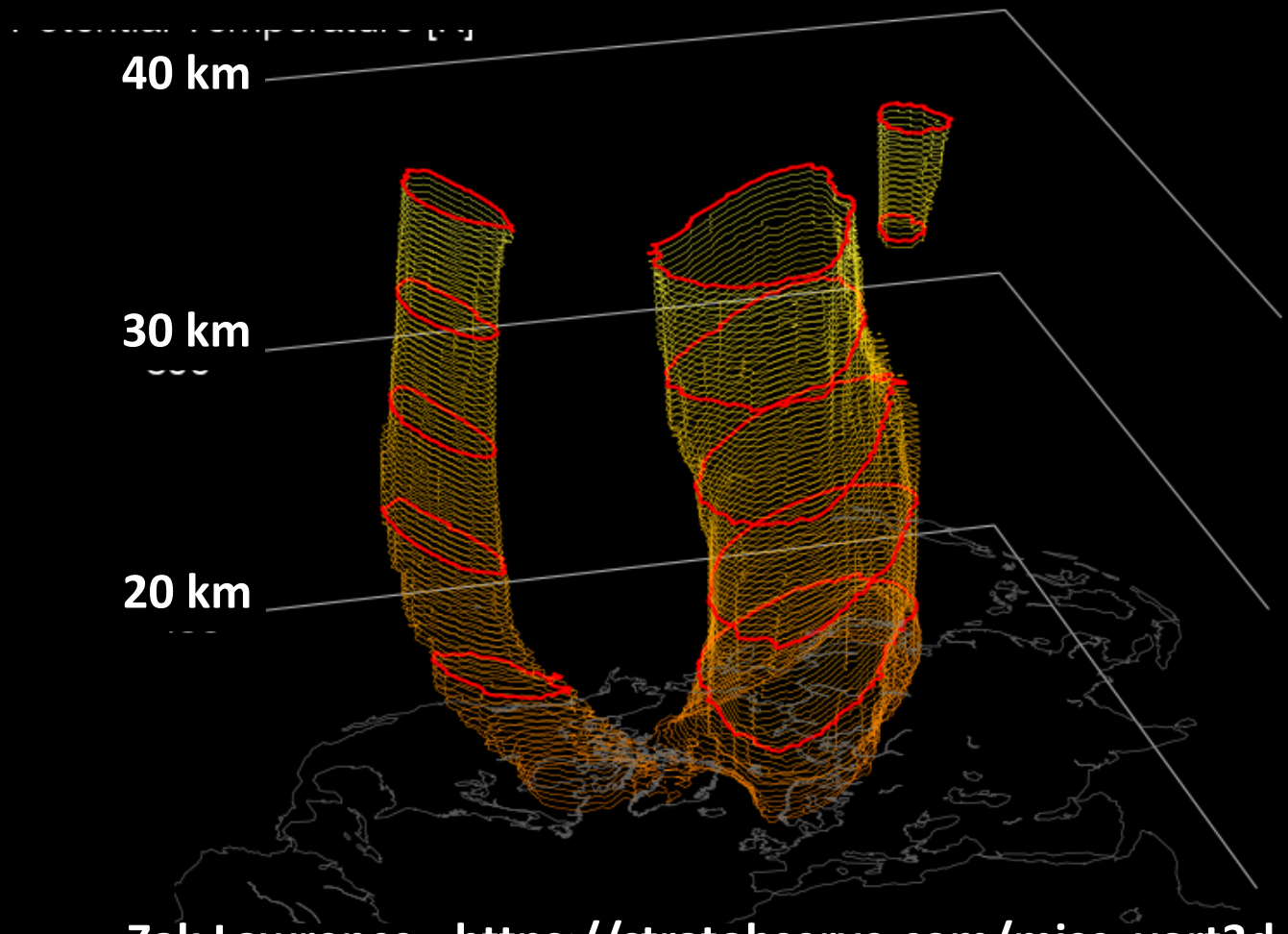


The Arctic Polar Vortex in Late February



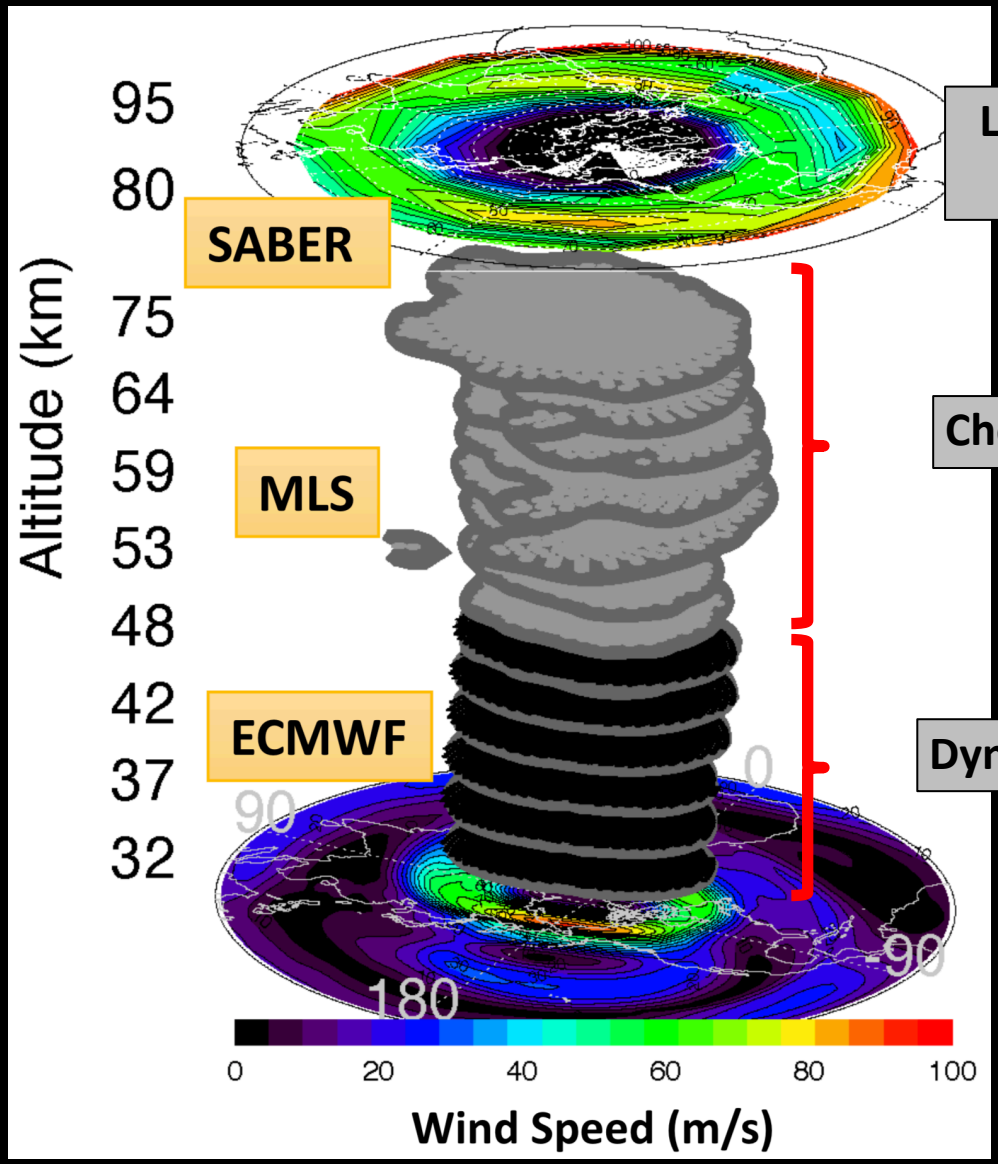
Zak Lawrence - https://stratobserve.com/misc_vort3d

The Arctic Polar Vortex today



Zak Lawrence - https://stratobserve.com/misc_vort3d

Defining the polar vortex from the tropopause to the mesopause



Lagrangian Coherent Structures

Harvey et al 2021

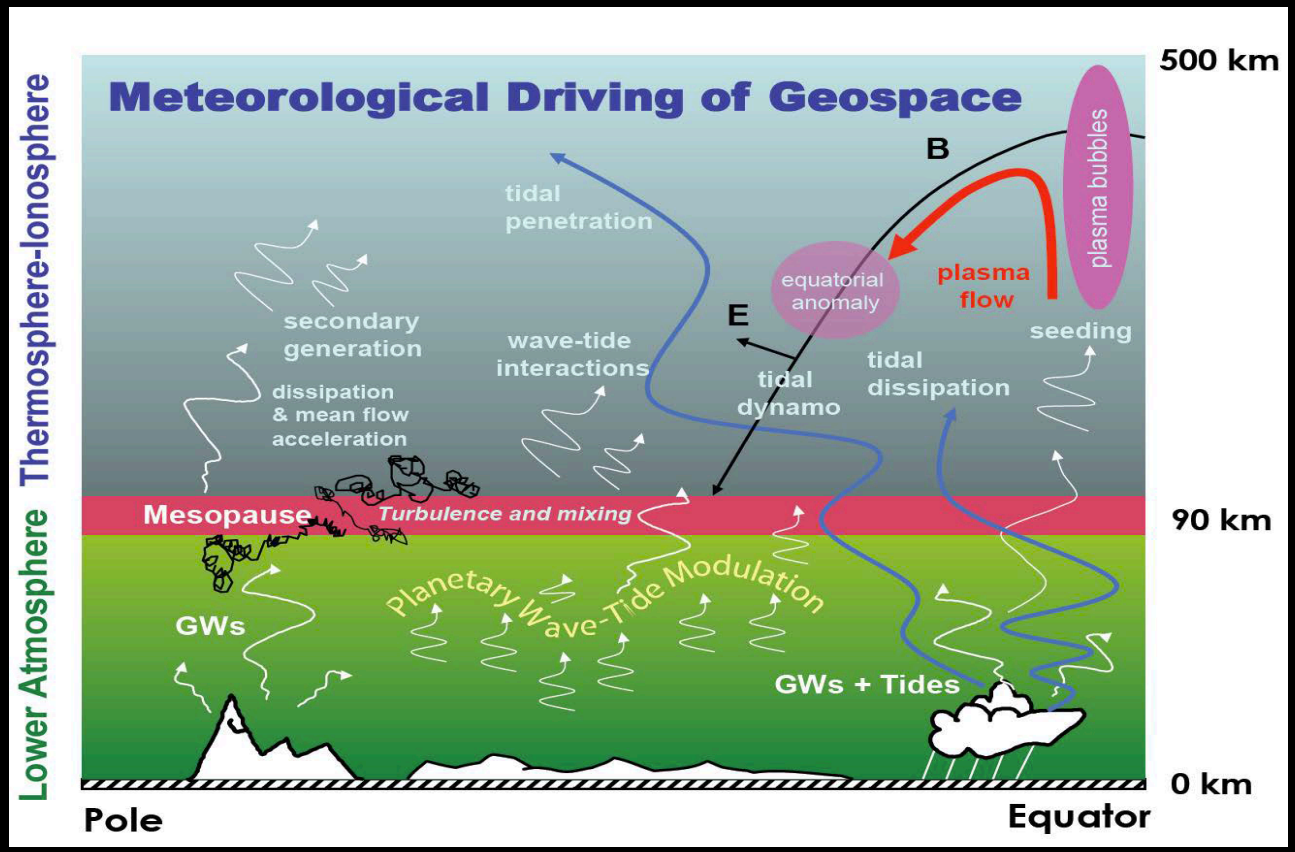
Chemical definition

Harvey et al 2015

Dynamical definition

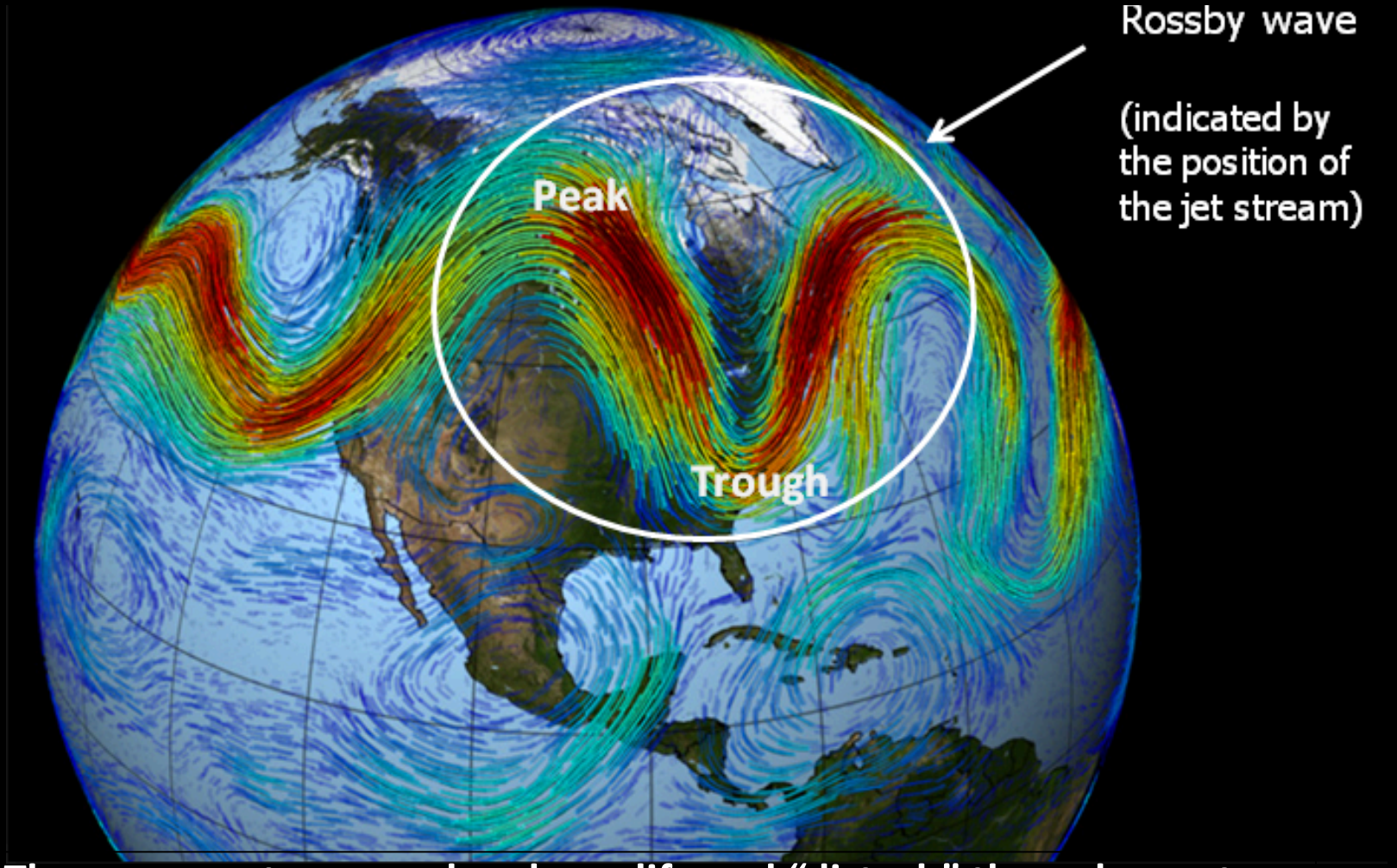
Harvey et al 2002

Lower Atmosphere Wave Impacts the Thermosphere and Ionosphere



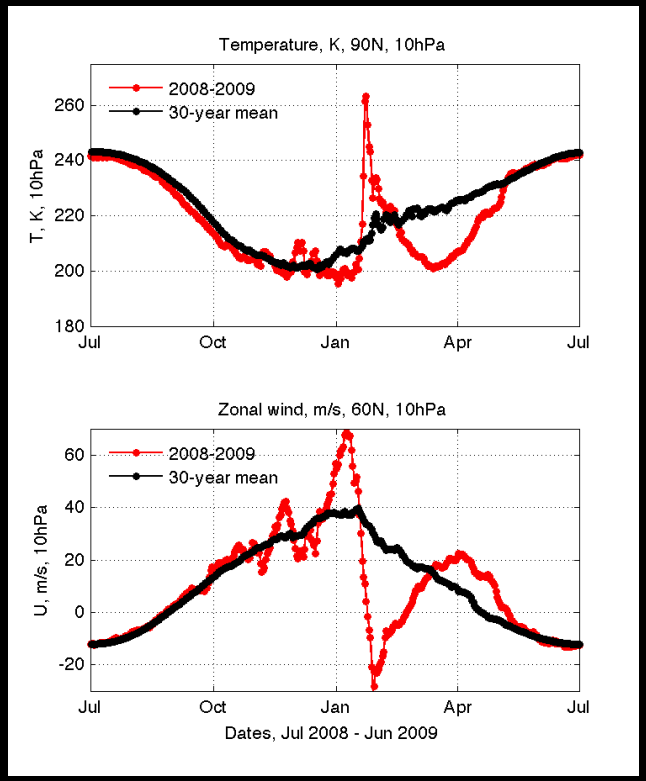
- Ionospheric electron density can strongly vary day-by-day
- Effects of waves generated in the lower atmosphere that propagate upward
- Planetary waves – 10-16 day, 5-6 day, 2-day
- Tidal waves – 24-hrs, 12-hrs, 8-hrs
- Gravity waves – variations with periods ~5mins – 6-8 hrs

Planetary waves form in the upper tropospheric jet stream due to weather systems below

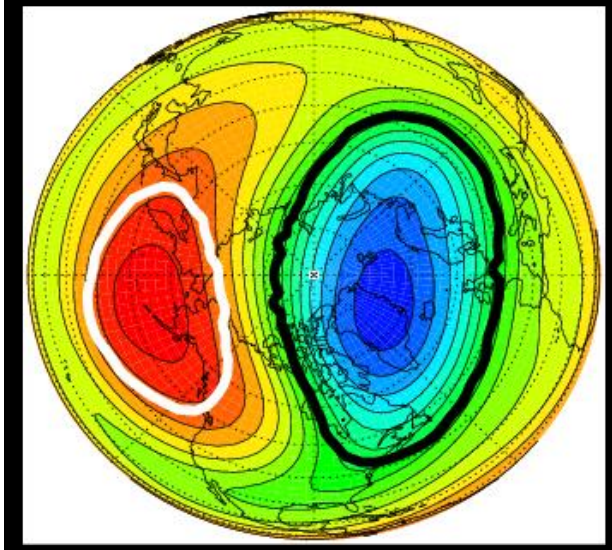


They propagate upward and amplify and "disturb" the polar vortex

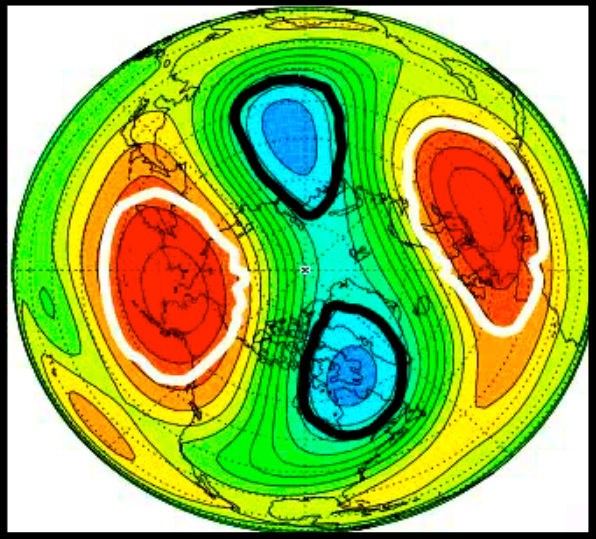
Sudden Stratospheric Warmings (SSWs) are large disruptions to the polar vortex



Vortex Displacement

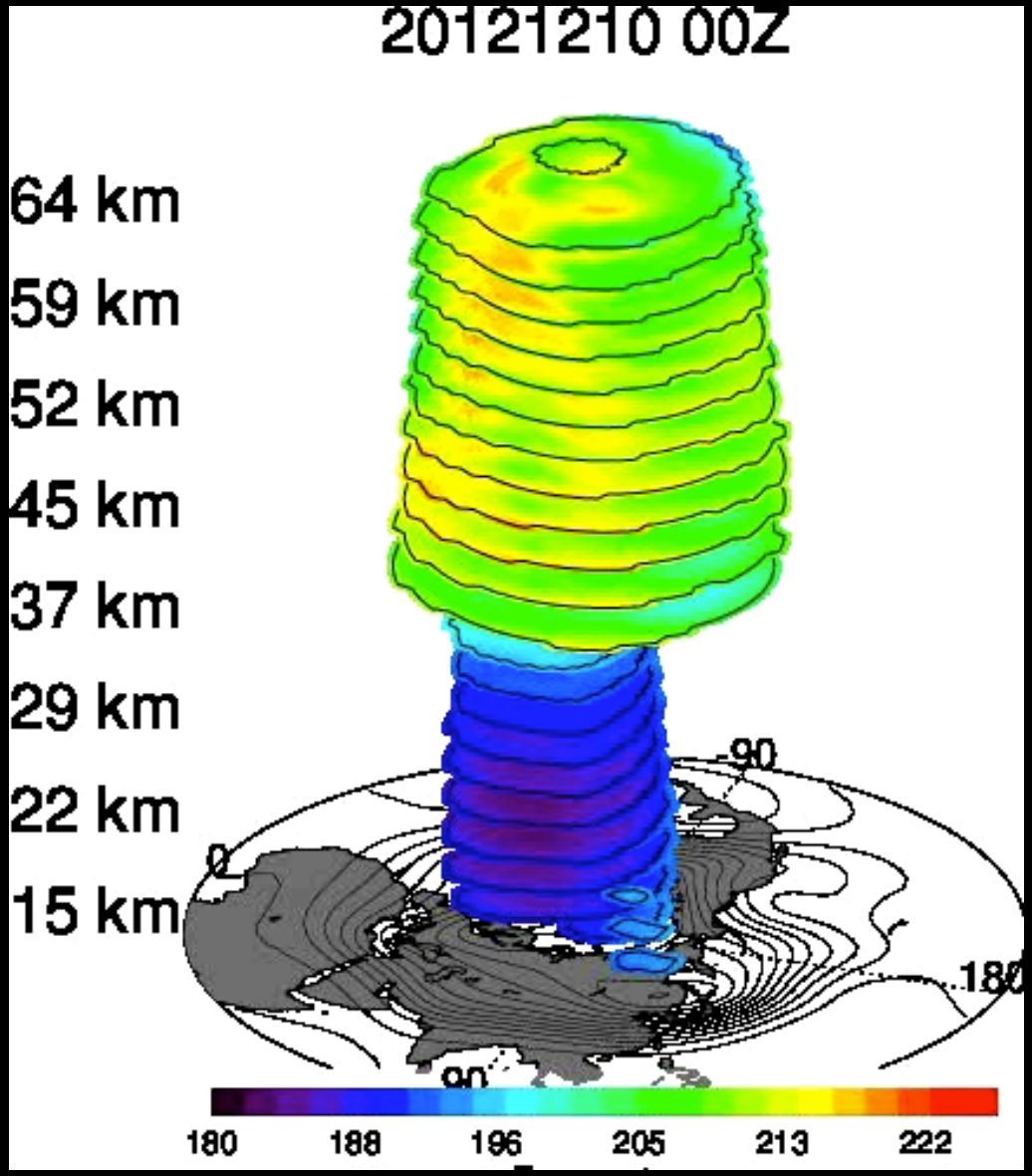


Vortex Split

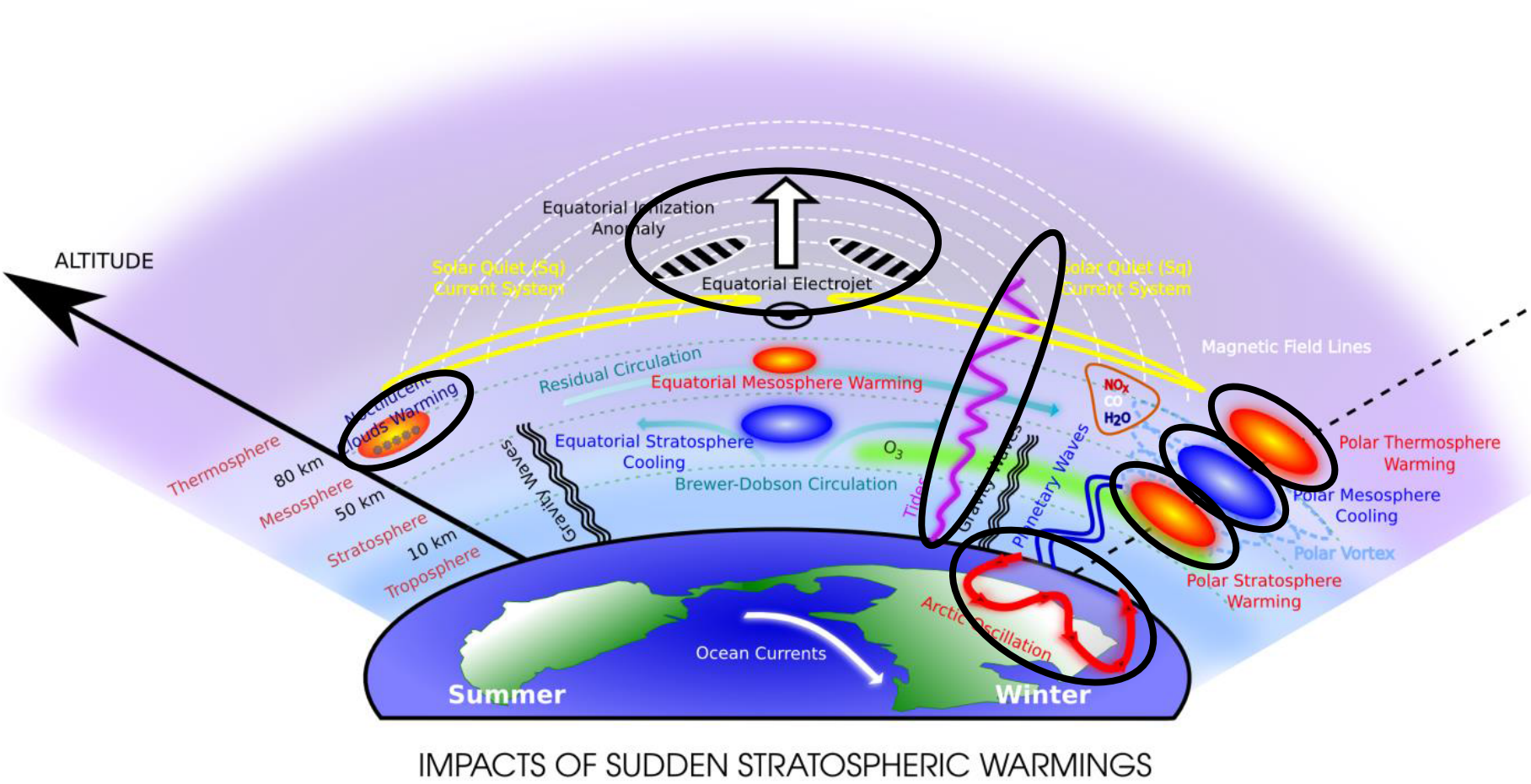


- Rapid increase in temperature >50K in the polar stratosphere
- Weakened or reversed zonal mean wind
- Anomalies can persist in the stratosphere (2 weeks +)
- SSW events occur 1-3 times per winter in the NH
- One per decade in the SH

4D Evolution of 2012-13 SSW



Effects of SSWs are observed throughout the ocean-atmosphere-ionosphere system



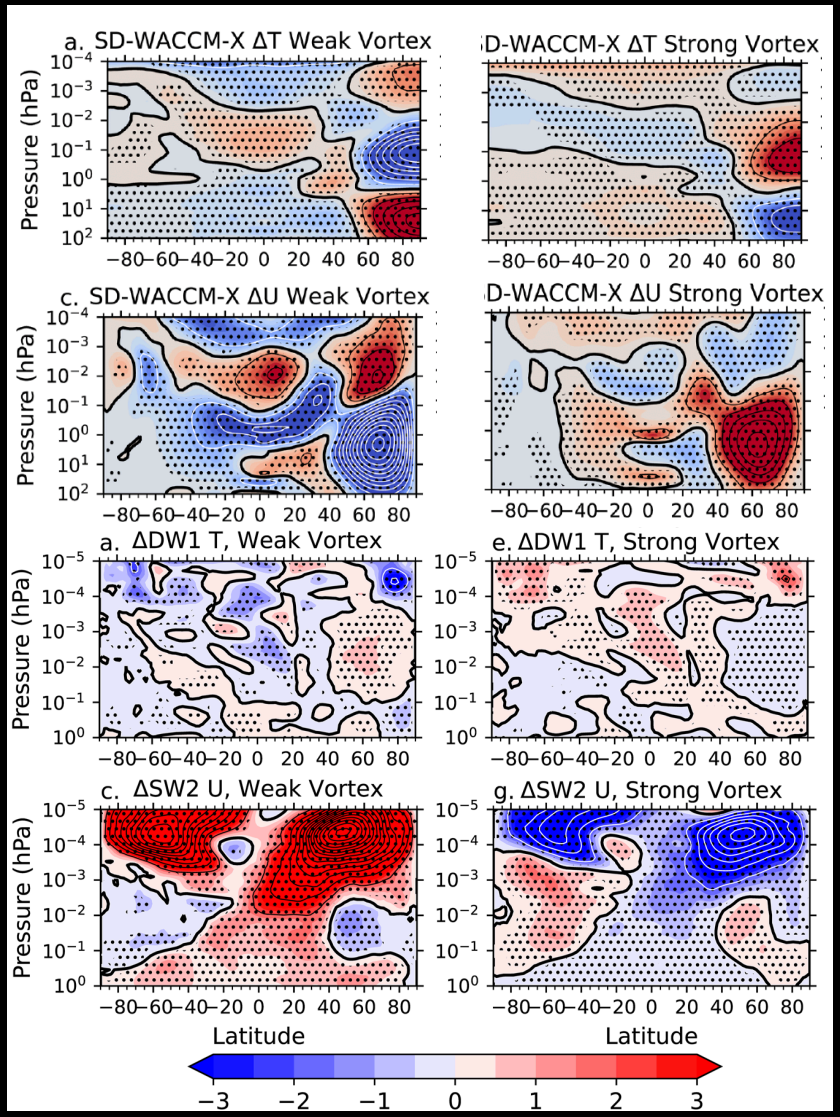
Pedatella et al. (2018) EoS

Harvey et al. 2025, submitted: Weak polar vortex events drive anomalies in MLT winds, PWs, and the SW2

- *SuperDARN zonal wind, meridional wind, SW2 and Q6DW amplitude*
- *SEAs centered on the onset dates of the 15 SSWs.*
- *Large event-to-event variability*
- *Weak U, poleward V, lagged SW2 and Q6DW amplification*
- *Consistent with WACCMX*

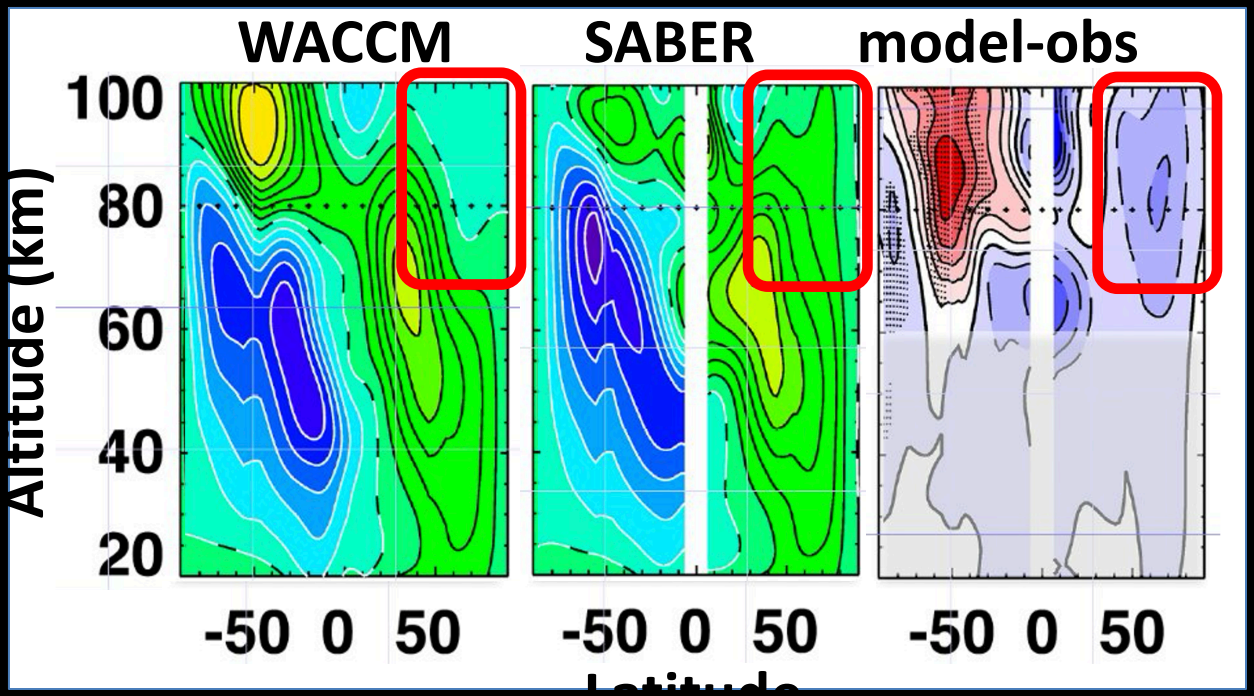
Courtesy of W. van Caspel

Pedatella & Harvey 2022: Weak and strong polar vortex events drive anomalies of the opposite sign in the MLT


a. SD-WACCM-X ΔT Weak Vortex
D-WACCM-X ΔT Strong Vortex
c. SD-WACCM-X ΔU Weak Vortex
D-WACCM-X ΔU Strong Vortex
a. ΔDW1 T, Weak Vortex
e. ΔDW1 T, Strong Vortex
c. ΔSW2 U, Weak Vortex
g. ΔSW2 U, Strong Vortex
Pressure (hPa)
Latitude
−80 −60 −40 −20 0 20 40 60 80
−3 −2 −1 0 1 2 3

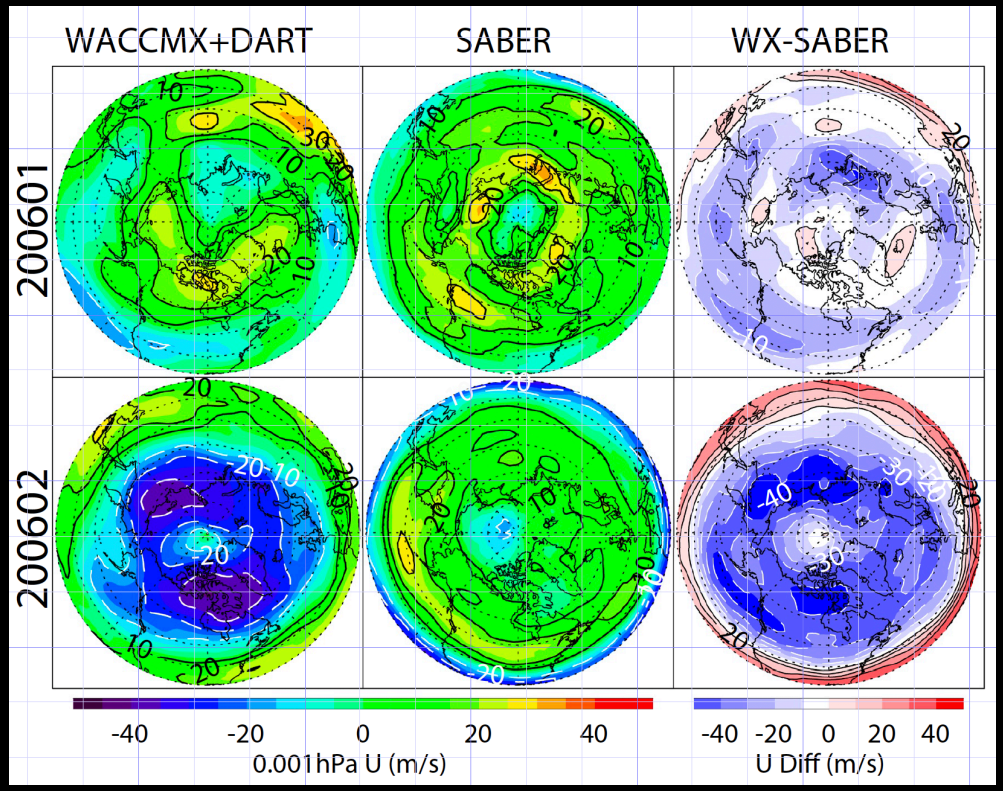
- T, U anomalies opposite for weak vs. strong but ~30%–40% smaller for strong polar vortex
- Migrating tide (DW1, SW2) anomalies opposite for weak vs. strong polar vortex but smaller for strong vortex
- Vortex strength is predictable 2 weeks in advance

Harvey et al. (JGR 2019): DJF mean winds blow in the wrong direction in the polar winter upper mesosphere of WACCM



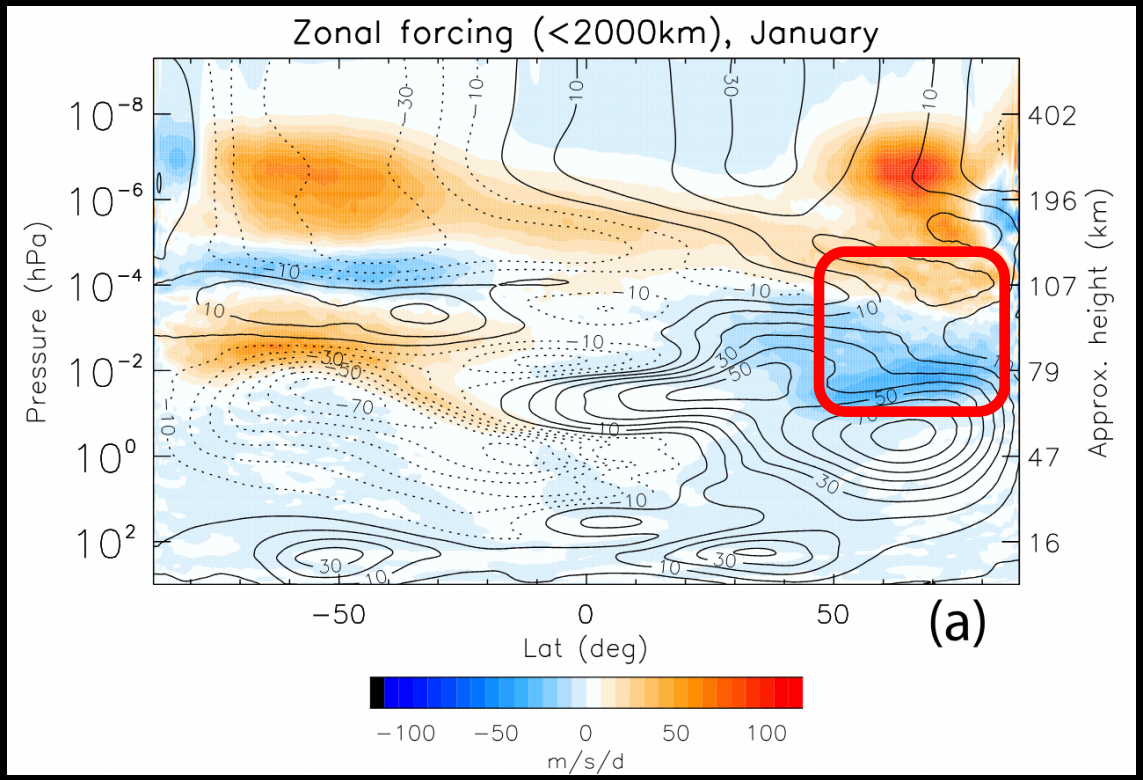
- SABER observations show westerly winds associated with the mesospheric polar vortex extend ~20 km higher than the model in polar winter

Harvey et al. (JGR 2022): Model wind bias occurs during strong polar vortex



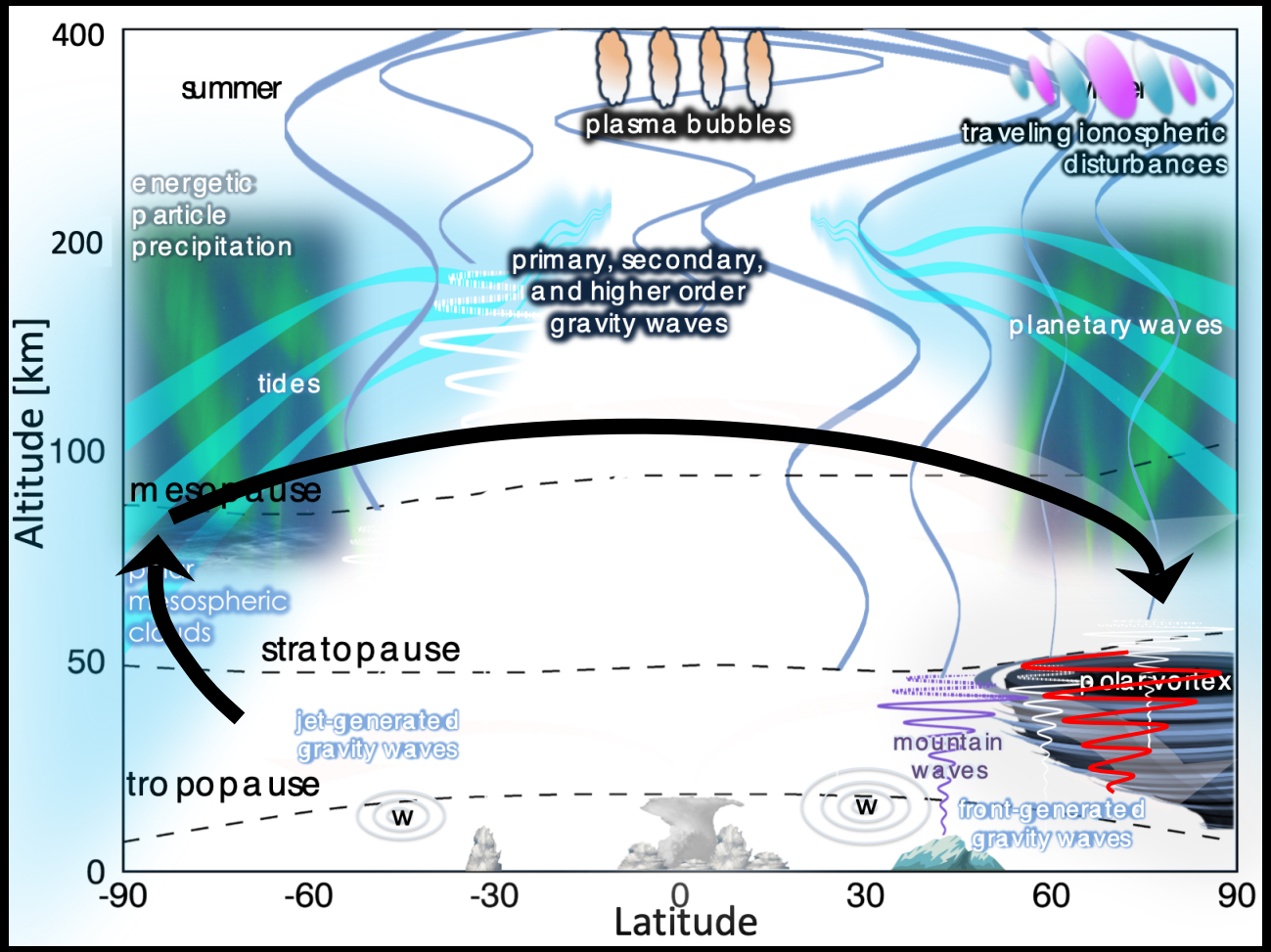
- Model zonal winds (left), SABER zonal winds (middle), difference (right)
- Weak polar vortex (top), Strong polar vortex (bottom)
- Zonal wind bias occurs during strong vortex conditions

Liu et al. (GRL 2024): High-res WACCMX resolves GWs that alter circulation and composition



- 25 km horizontal x 0.1 scale height vertical resolution
- GW parameterization turned off
- Improved GW forcing improves thermospheric circulation
- The circulation changes lead to improved thermospheric O/N_2 and NO

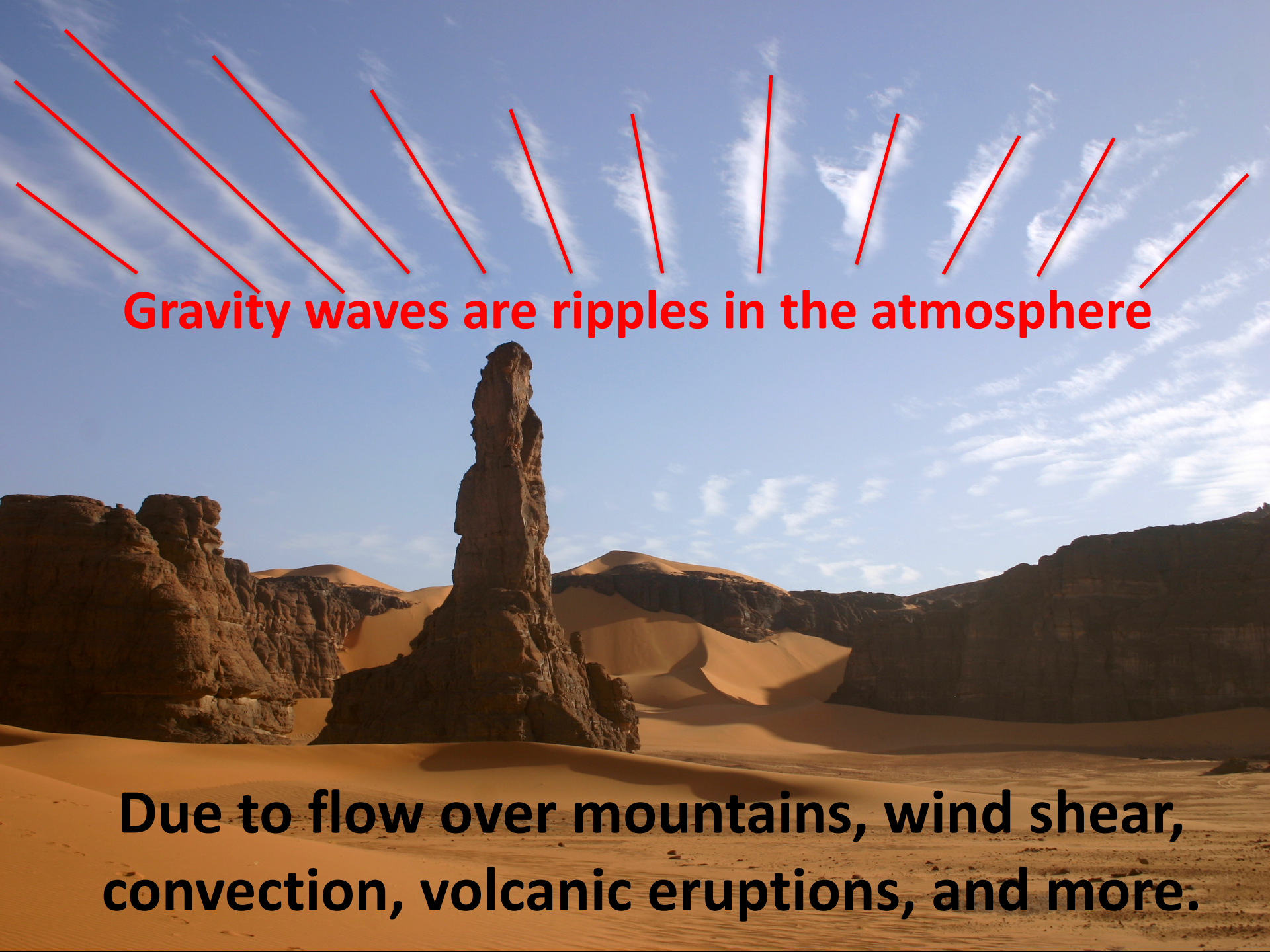
Mean meridional circulation, polar vortex, waves, and connections to the IT



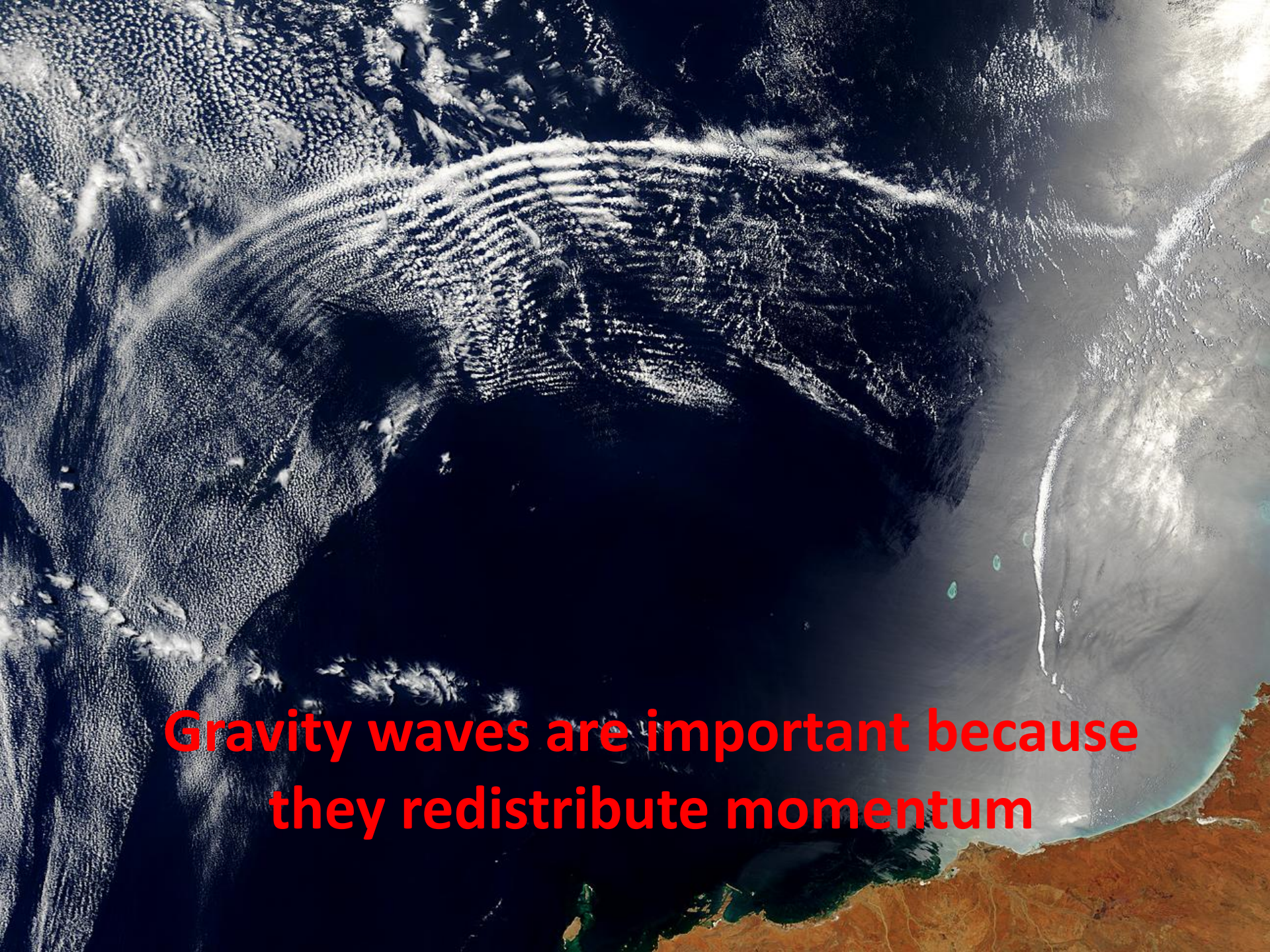
Top-down

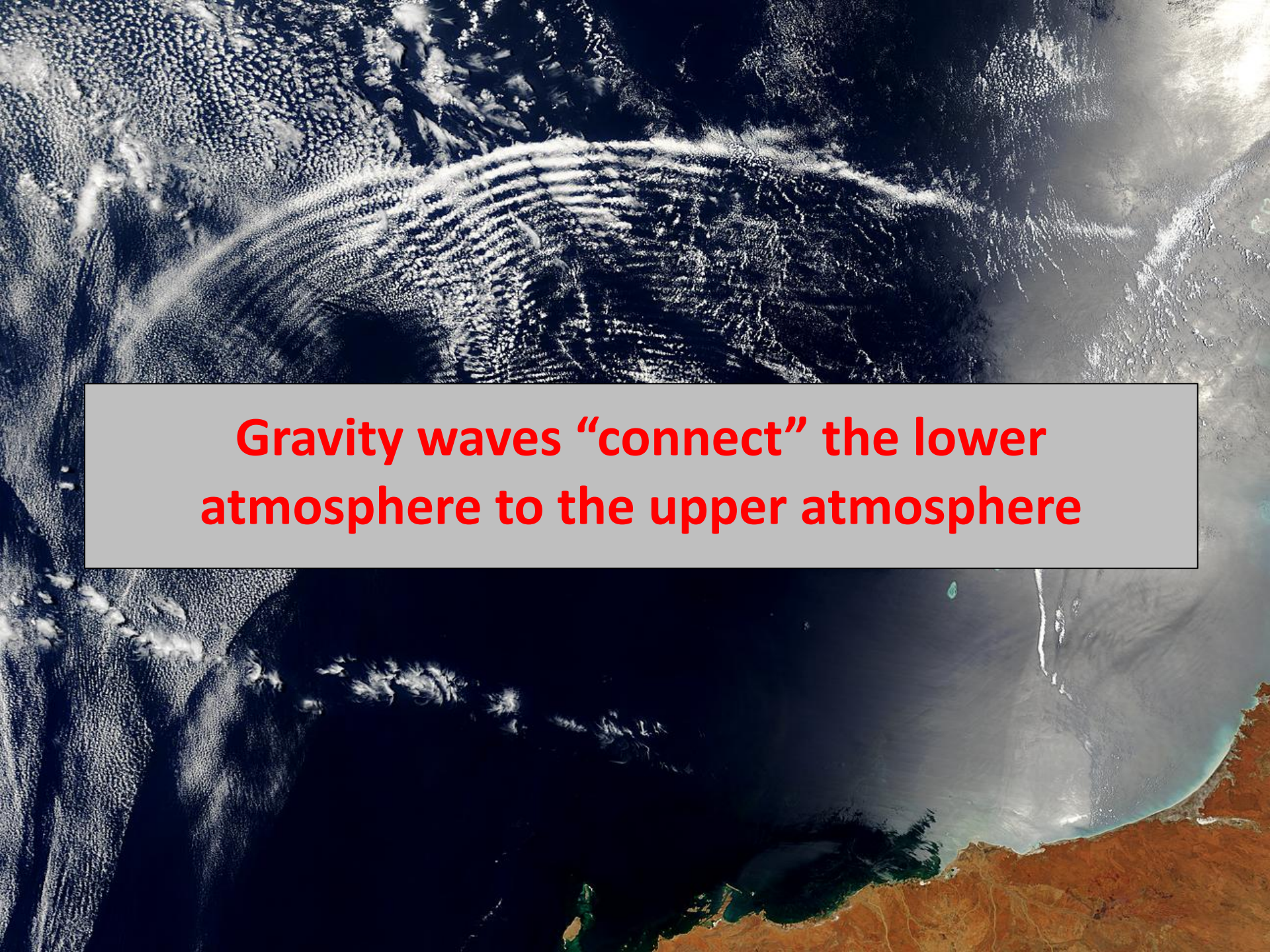
Bottom-Up

Courtesy of Laura Holt


Gravity waves are ripples in the atmosphere
Due to flow over mountains, wind shear, convection, volcanic eruptions, and more.

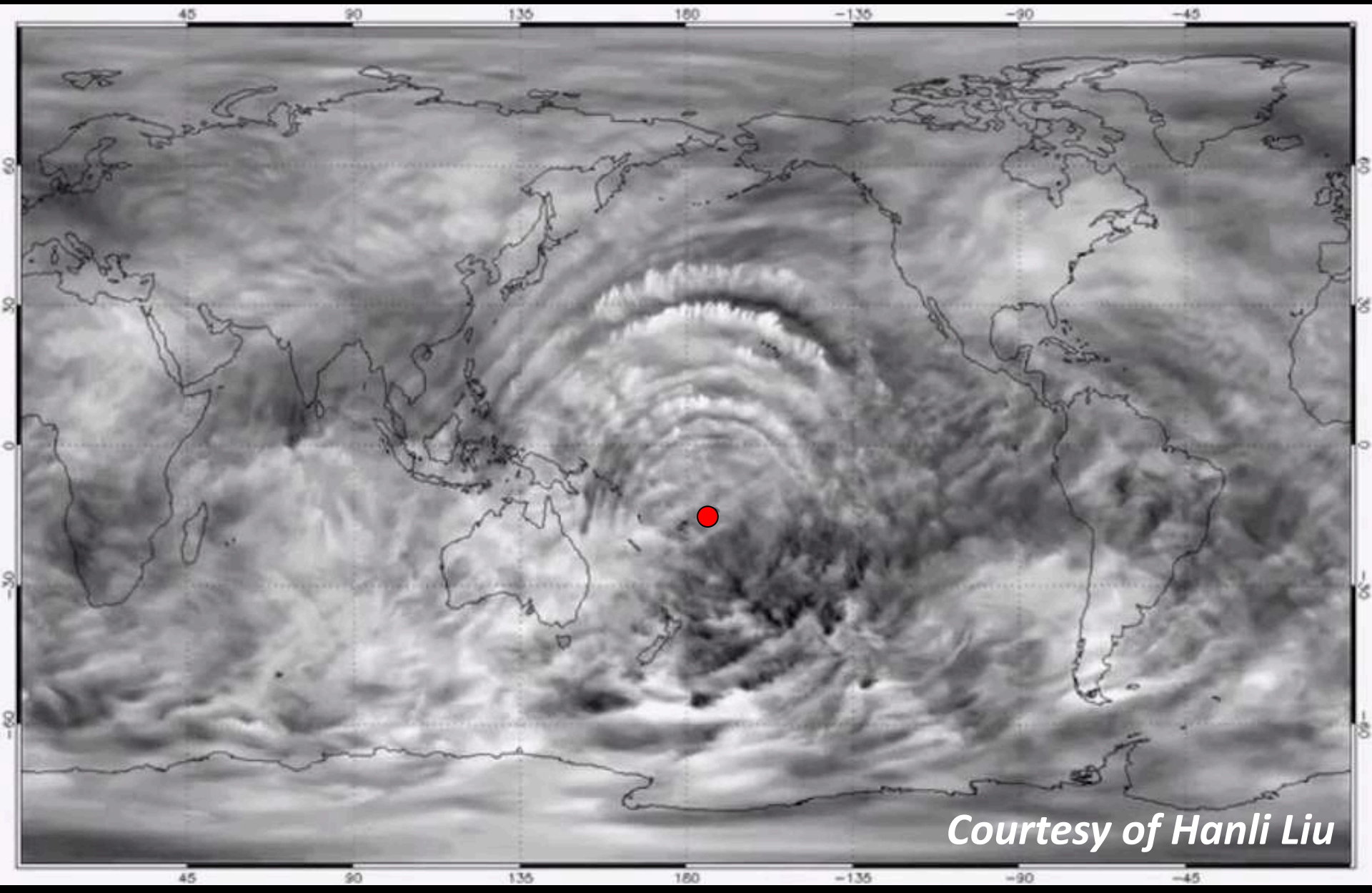
Gravity waves are visible in
cloud patterns


Gravity waves are important because
they redistribute momentum

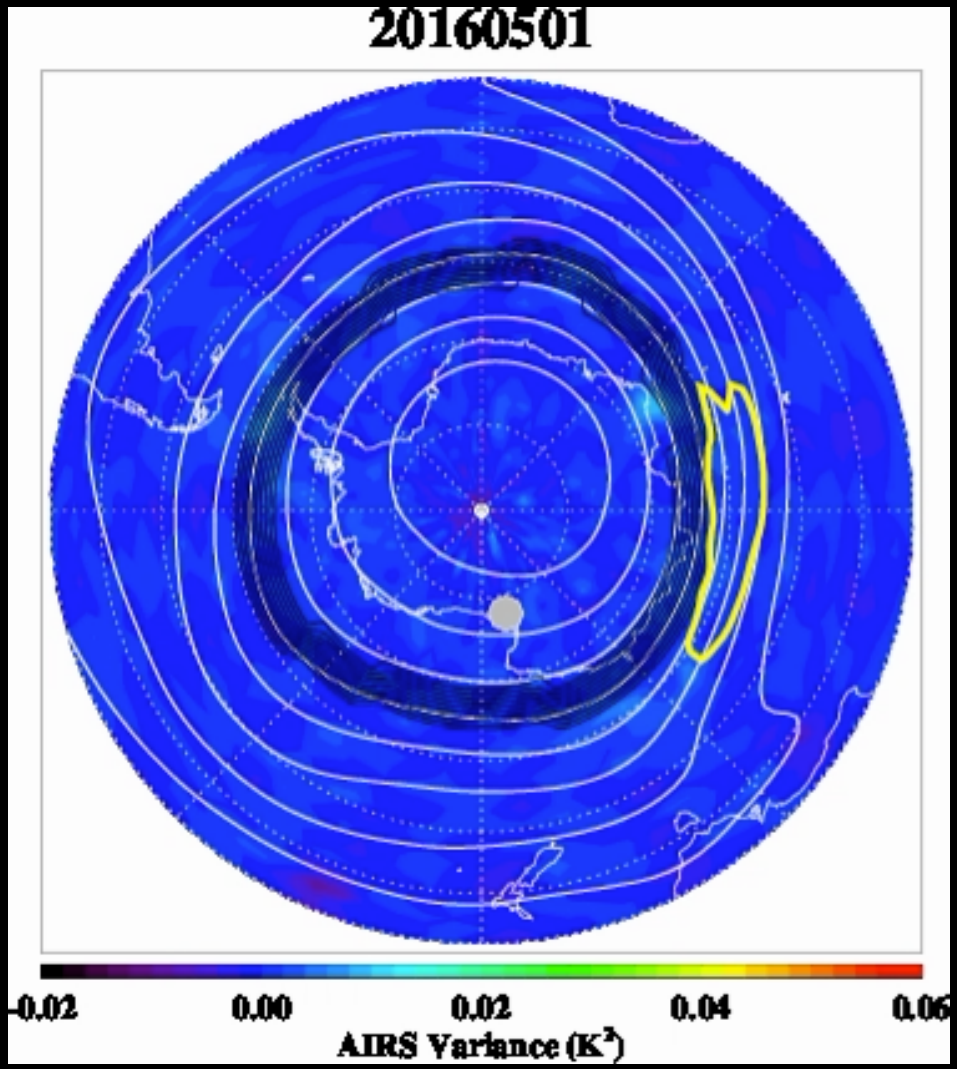

Gravity waves “connect” the lower atmosphere to the upper atmosphere

Even small mountainous islands
are important

Convection from this tropical cyclone is “felt” at 100 km!

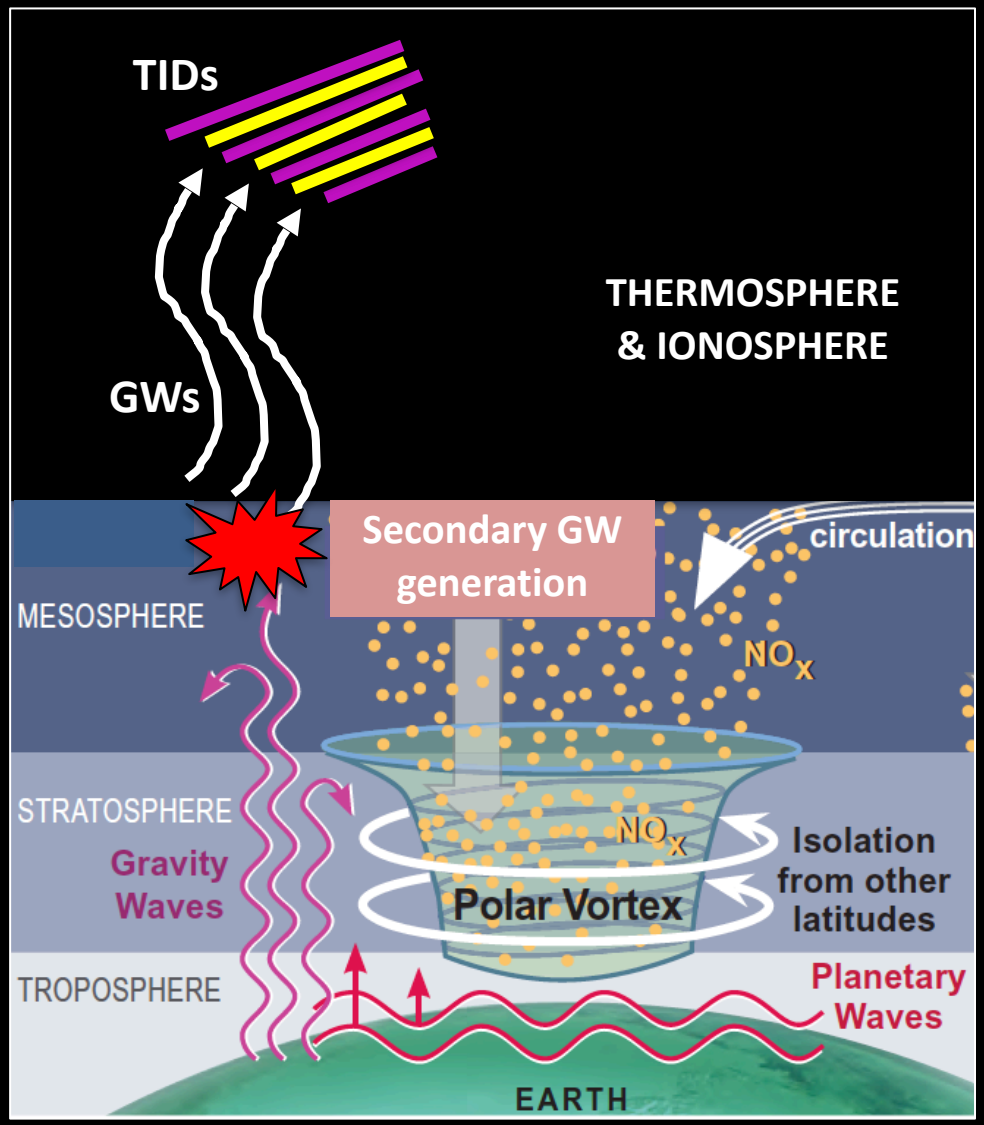


AIRS shows high gravity wave variance at the vortex edge



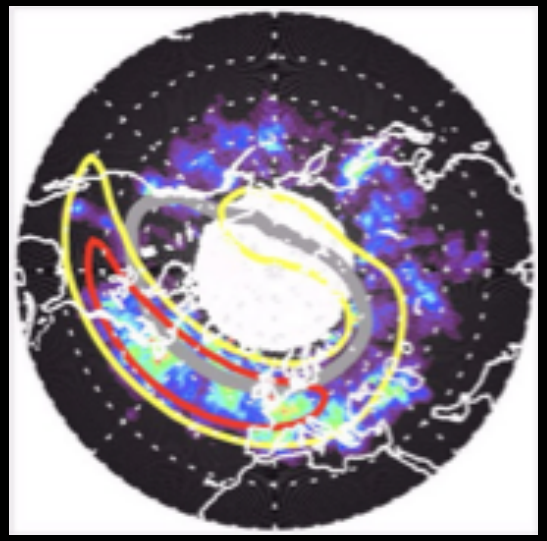
Motivation: GW activity during strong vortex times has been shown to lead to more TIDs

- Frissell et al., JGR 2016: Daytime winter MSTIDs occur more often when the polar vortex is strong
- Harvey et al., JGR 2023: PW patterns in GWs; GWs and TIDs reduced when vortex weak
- Becker et al., JGR 2022: GWs to TIDs via MSVC, patterns modulated by tides, amplitudes reduced when vortex is weak
- Vadas et al., JGR 2025: GWs from vortex jet lead to TIDs
- Derghazarian et al., submitted: GWs lead to TIDs across the hemisphere
- Frissell et al., 2025 in prep: Multi-year Climatology of MSTIDs
- Vortex strength improves ionospheric predictability



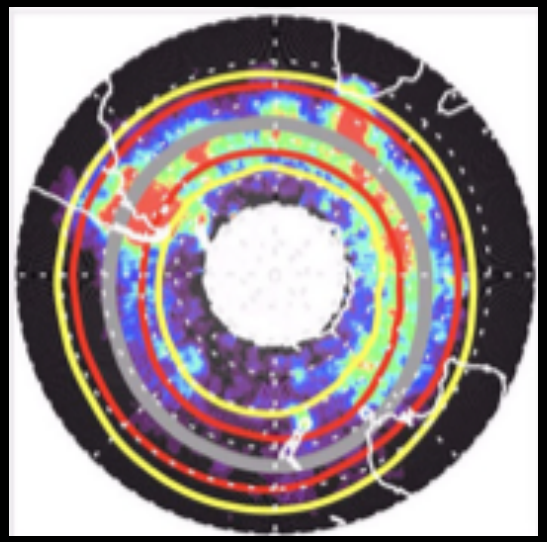
Harvey et al. (JGR 2023): Longitudinal asymmetries in winter GW activity

Dec 2020



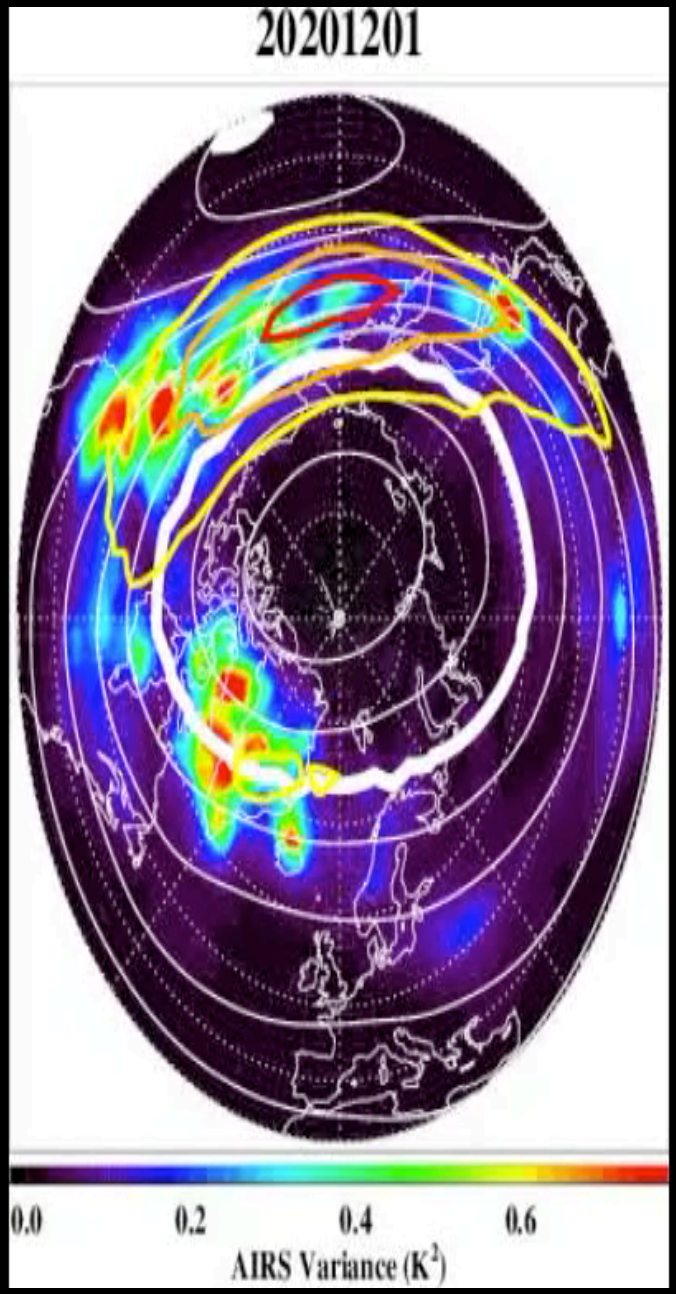
- Max GW variances and wind speed at the vortex edge
- NH: Max GW variances from North America to Europe over the Atlantic

Jun 2020



- SH: Max GW variances from South America to Australia over the Atlantic/Indian
- PW-1 patterns in GW activity

AIRS GW variance and the Arctic vortex 2021

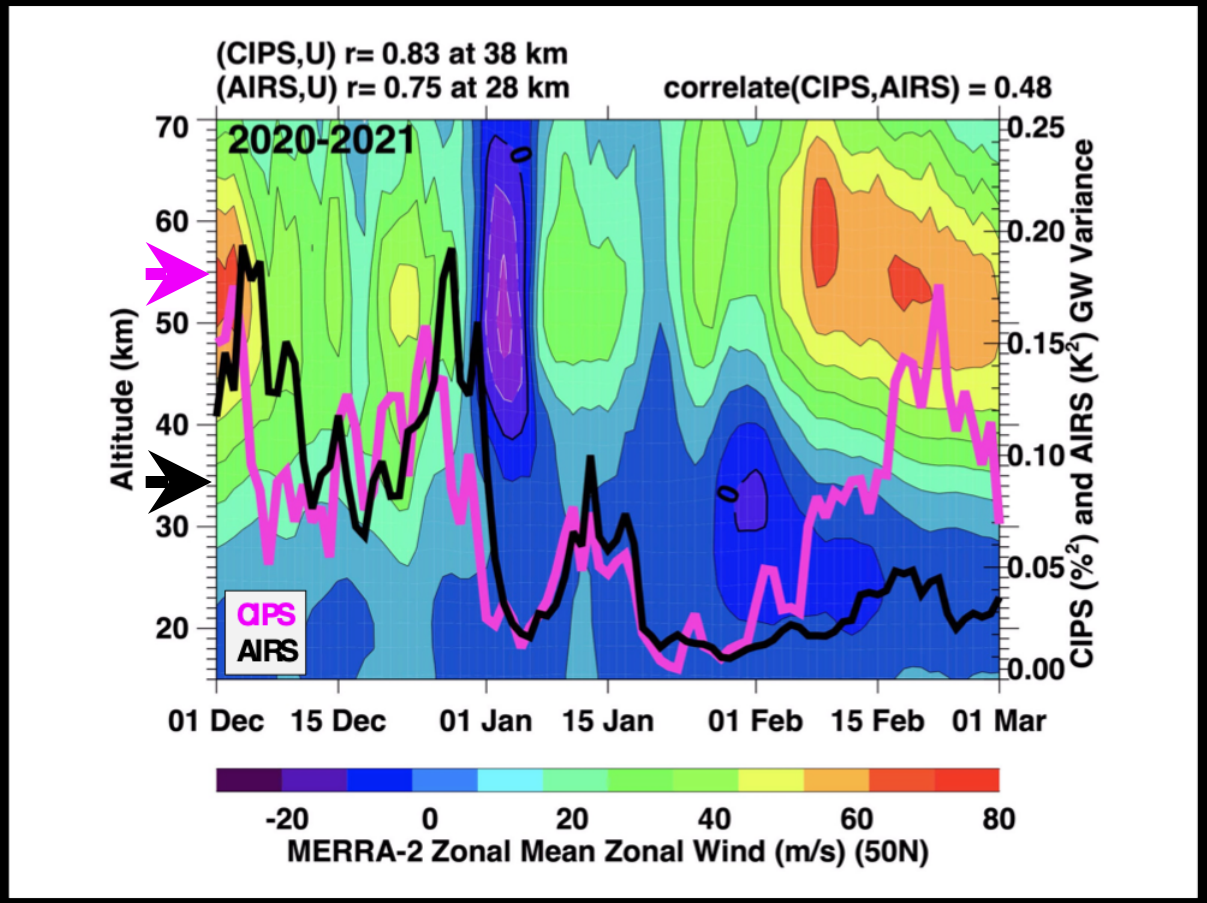


- Dec 2020 – Jan 2021
- Solid white = Arctic vortex
- Red contour = 100 m/s

- High GW variance in the vortex jet region

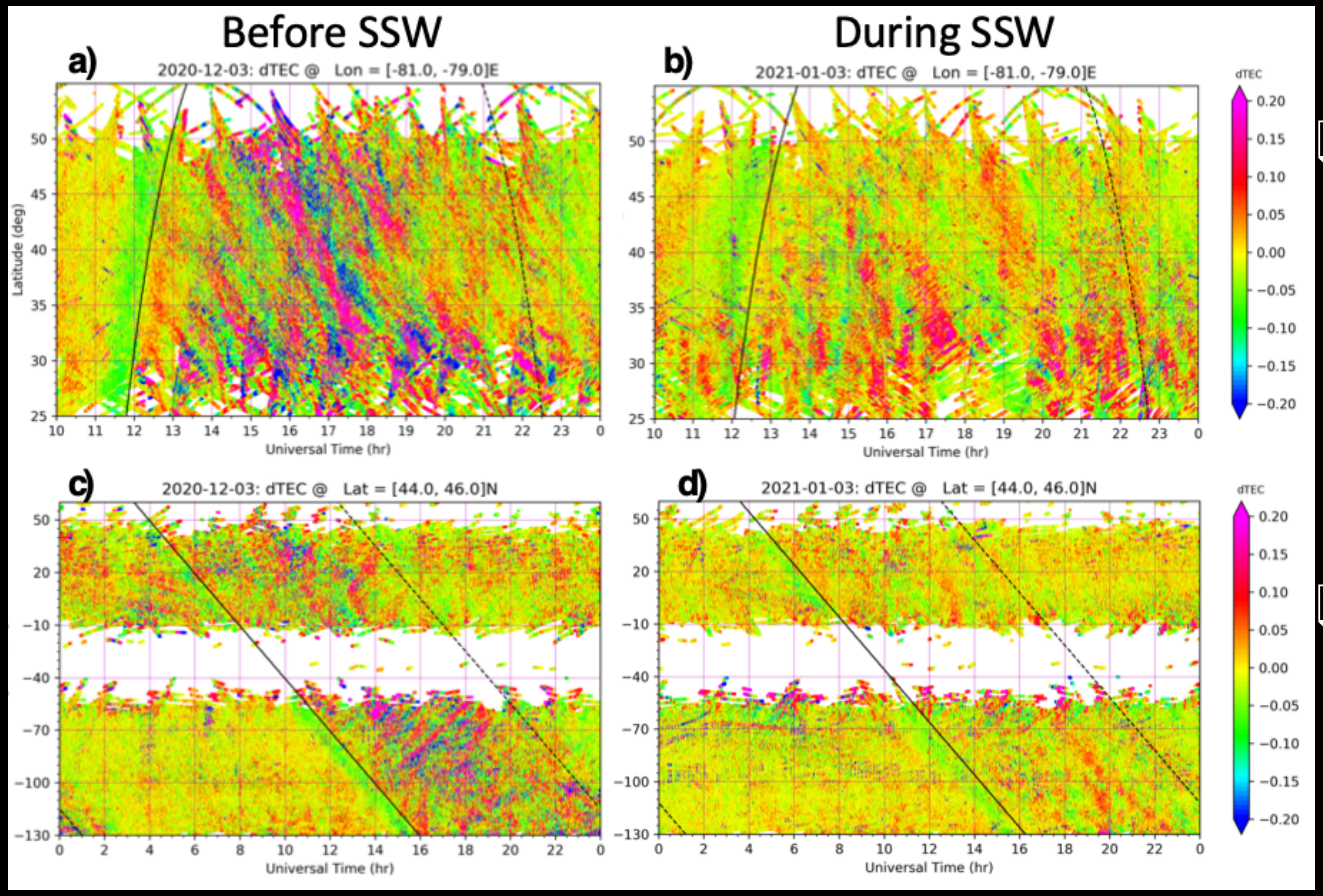
- GW suppression during the 2021 January SSW

GWs suppressed during 2021 SSW



- Consistent with previous studies, high GW activity when background winds are fast
- GW suppression during the SSW in early January

Variations in GWs lead to modulations in TIDs



- Latitude-UT and Longitude-UT plots of dTEC before and during SSW
- TIDs reduced by 75% during SSW

JGR Atmospheres

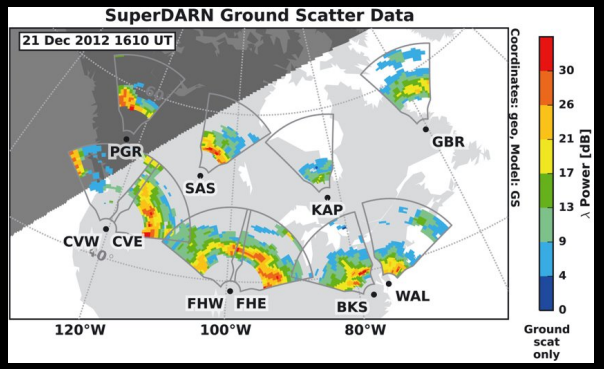
Research Article | Full Access

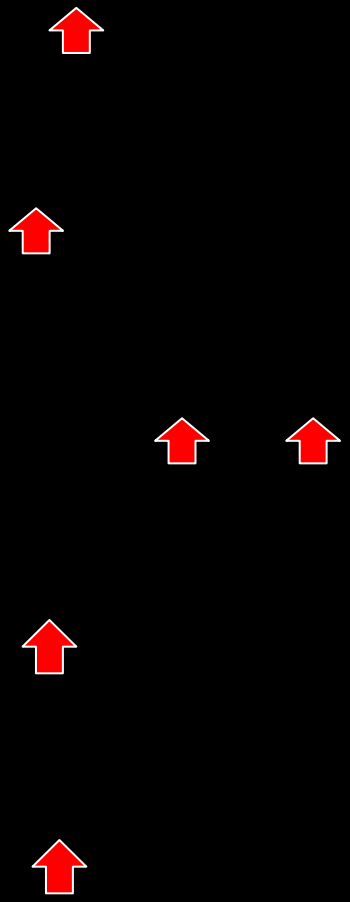
CIPS observations of gravity wave activity at the edge of the polar vortices and coupling to the ionosphere

V. L. Harvey, C. E. Randall, L. P. Goncharenko, E. Becker, J. M. Forbes, J. Carstens, S. Xu, J. A. France, S.-R. Zhang, S. M. Bailey

First published: 13 June 2023 | https://doi.org/10.1029/2023JD038827

Frissell et al. , in prep: MSTID Activity Modulated Following SSWs

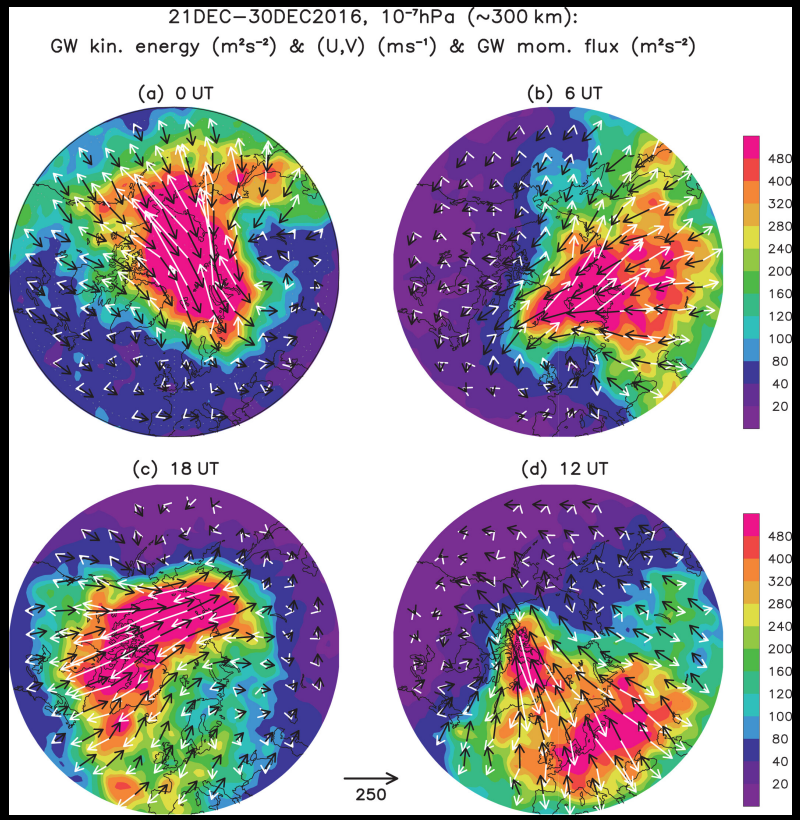




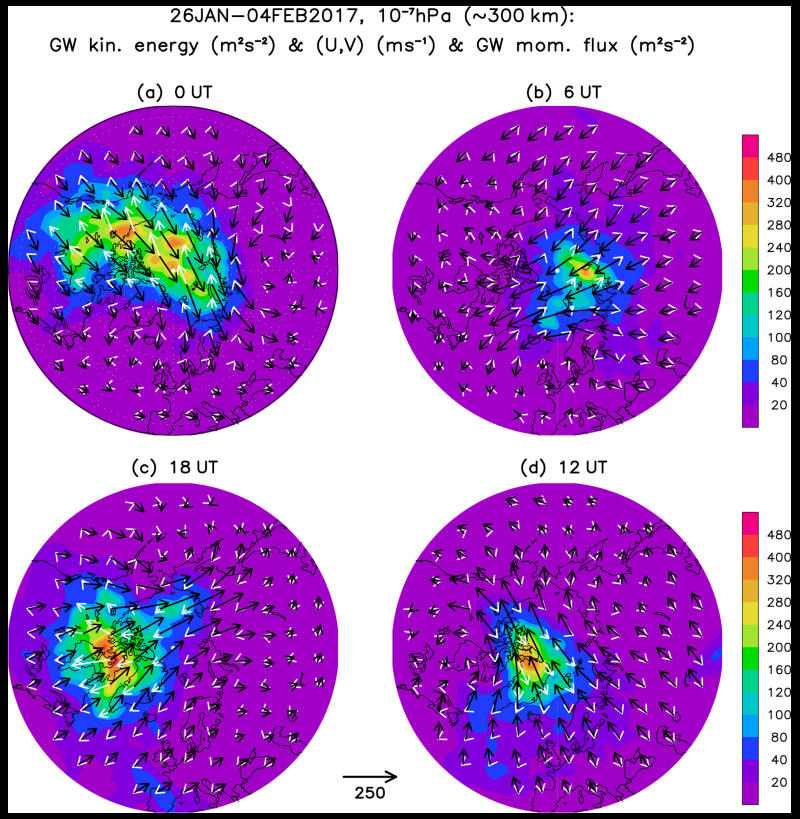
- LT-Time plots of MSTID index derived from SuperDARN over 5 Arctic winters
- MSTIDs reach a minimum 5-10 days after SSW onset
- Exact coupling mechanism(s) TBD

Becker et al. (JGR 2022): Thermosphere GW activity correlated with vortex strength

Strong Vortex



Weak Vortex

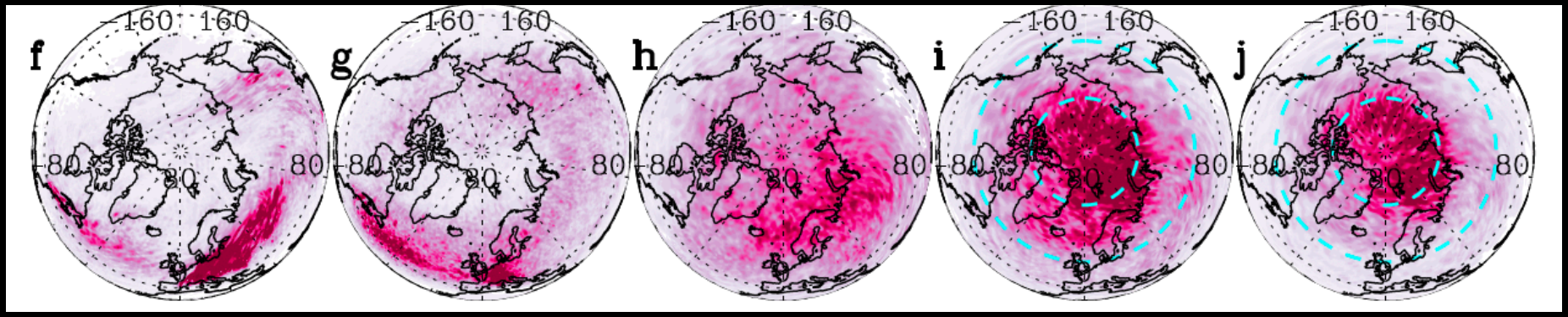


- Thermosphere GW spatial patterns influenced by DW1
- Thermosphere GW amplitude weaker for weak vortex

Vadas et al. (JGR 2024): GWs from vortex jet led to TIDs that could be mistaken as being forced from above

HIAMCM Density Perturbations

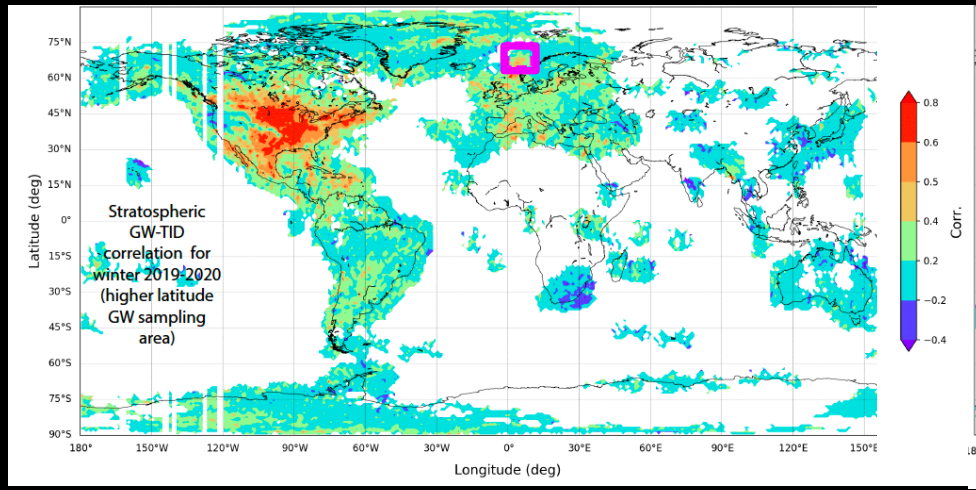
40 km **70 km** **140 km** **260 km** **360 km**



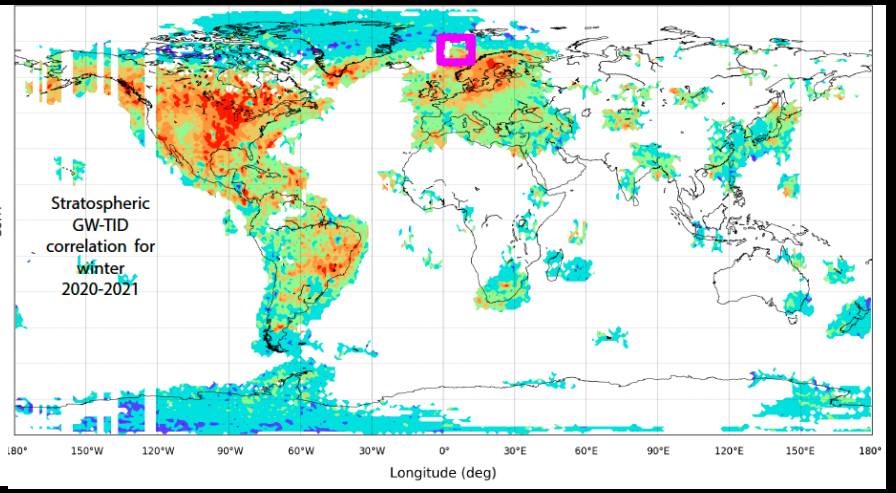
- Primary GW hotspot in stratosphere over Europe, south of 60N
- No GWs generated by geomagnetic forcing
- All GWs are generated/modulated by the polar vortex
- In thermosphere, GWs propagate from high to low lats during daytime thus resemble those forced from geomagnetic activity

Derghazarian et al. , submitted: GWs in vortex jet hotspot most highly correlated with MSTIDs across the hemisphere

Strong Vortex


Stratospheric GW-TID correlation for winter 2019-2020 (higher latitude GW sampling area)
Latitude (deg)
Longitude (deg)
Corr.

Weak Vortex



- **Strong vortex:** TIDs over mid-lat N. America most highly correlated with the sampled GWs
- **Weak vortex:** high correlations between GWs in the vortex jet hotspot and MSTIDs are spread across many lats and lons
- Next: explore GW-tidal interactions, perform GW ray-tracing

Summary

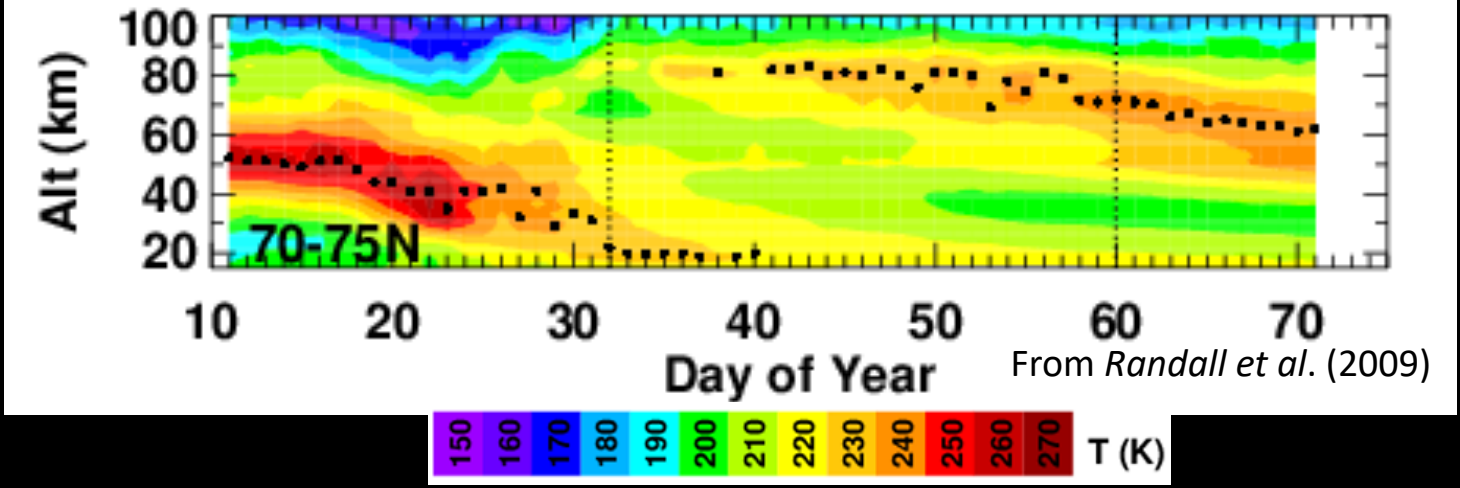
- ❑ The winter polar vortex is a fast jet stream in the stratosphere and mesosphere encircling a region with confined descent.
- ❑ PWs, SSWs result in catastrophic breakdown of the vortex
- ❑ SSWs drive variability in the whole atmosphere-ionosphere system.
- ❑ Opposite weak/strong vortex anomalies in MLT temps, winds, tides
- ❑ Added predictability to the upper atmosphere.
- ❑ High GW activity at the vortex edge. PWvsignatures in wintertime GW distributions
- ❑ DW1 influences GW spatial patterns in the thermosphere
- ❑ GWs and TIDs suppressed when vortex is weak
- ❑ Polar vortex is a GW source and associated TIDs may be mistaken as being forced from above
- ❑ GW hotspots in the stratosphere lead to TIDs at remote locations
- ❑ More work needs to be done!

Thank You!

Extra Slides

Example of an Elevated Stratopause (ES) event

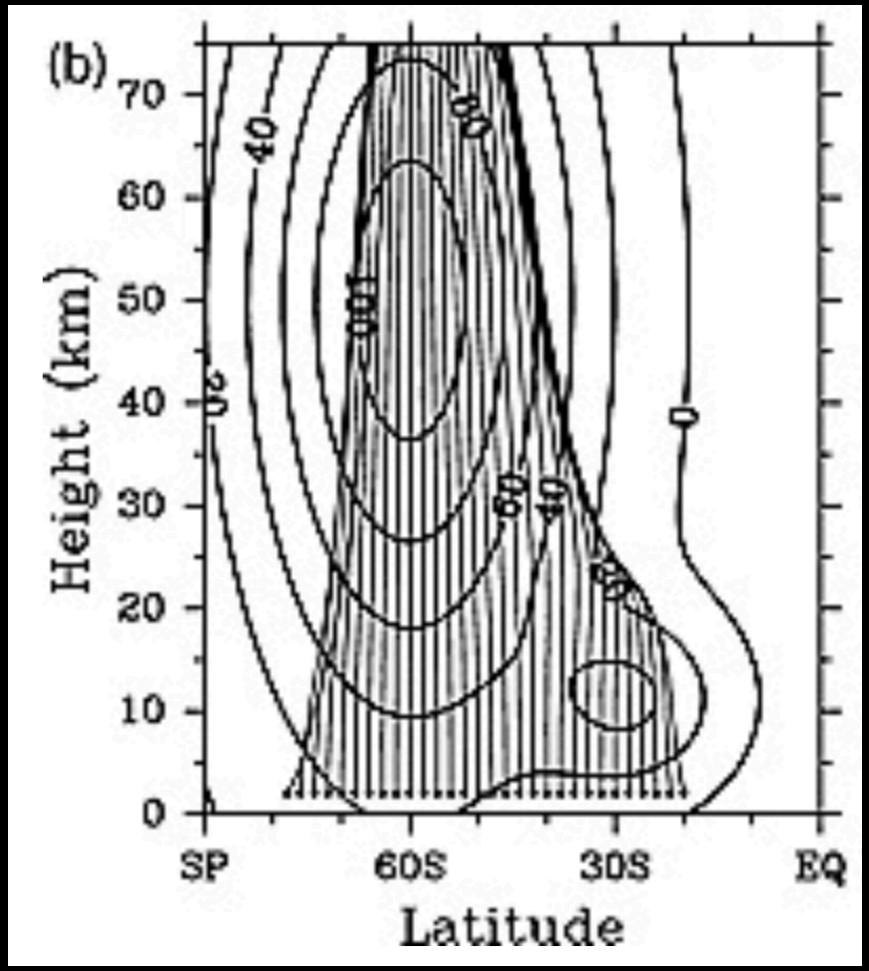
SABER temperature in 2009



From *Randall et al*. (2009)

- PWs reverse winds, filter GWs, and lead to convergence and descent over pole
- ES due to adiabatic warming in "mesosphere"
- Enhanced GW-driven descent transports NOx from MLT to the stratosphere

Why is there high GW activity in the vortex jet?

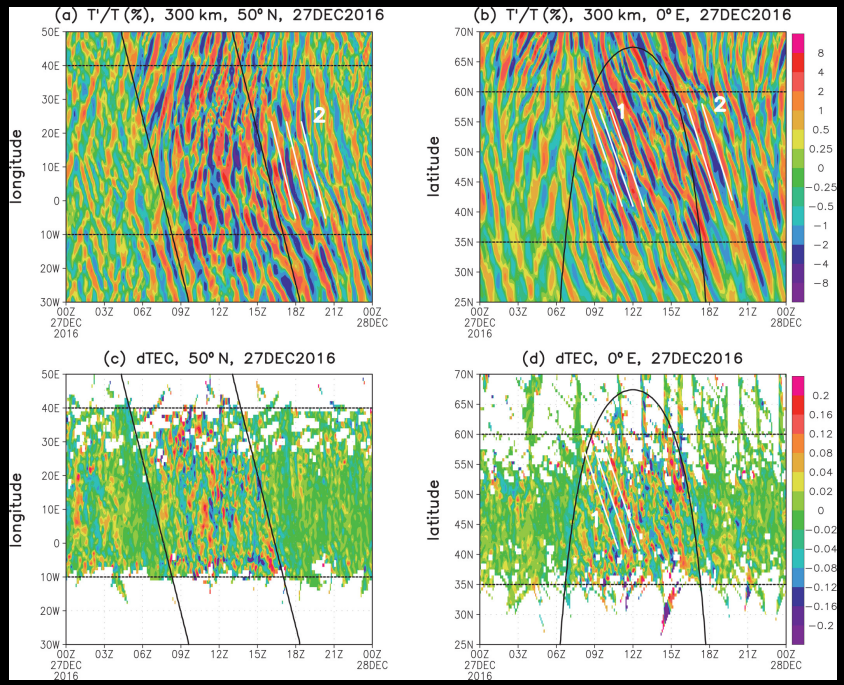


GW ray paths in idealized background westerly winds (Sato et al. 2009)

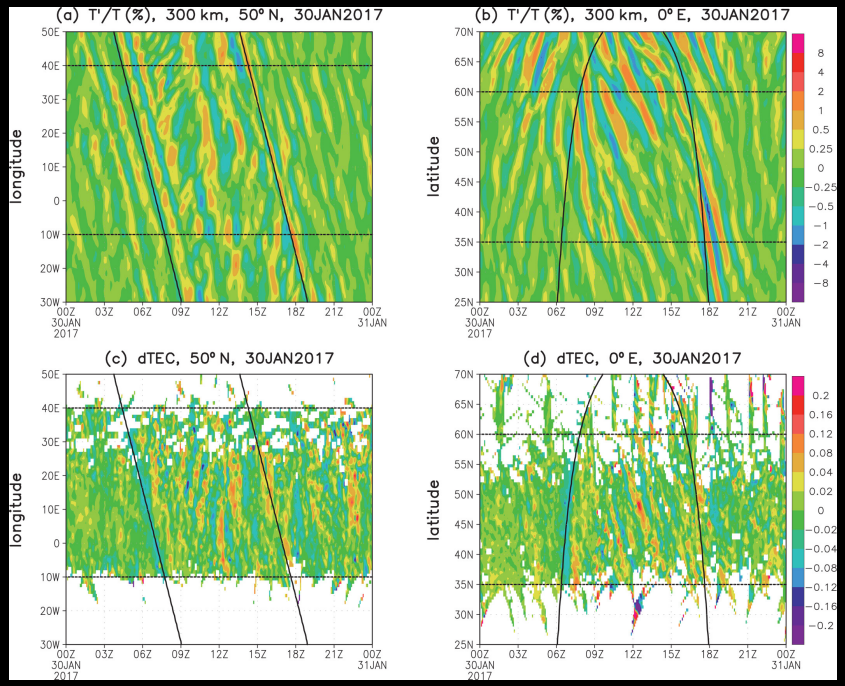
1) Surface sources below and focusing. GW propagation directions are focused toward faster wind speeds
2) Fast winds make GWs visible. GWs are refracted to longer vertical wavelengths, so they can grow to larger amplitudes before breaking (observational filter)
3) They are they generated there. Dynamic instabilities due to wind shear or spontaneous adjustment or as secondary GWs generated by breaking primary GWs above the jet core

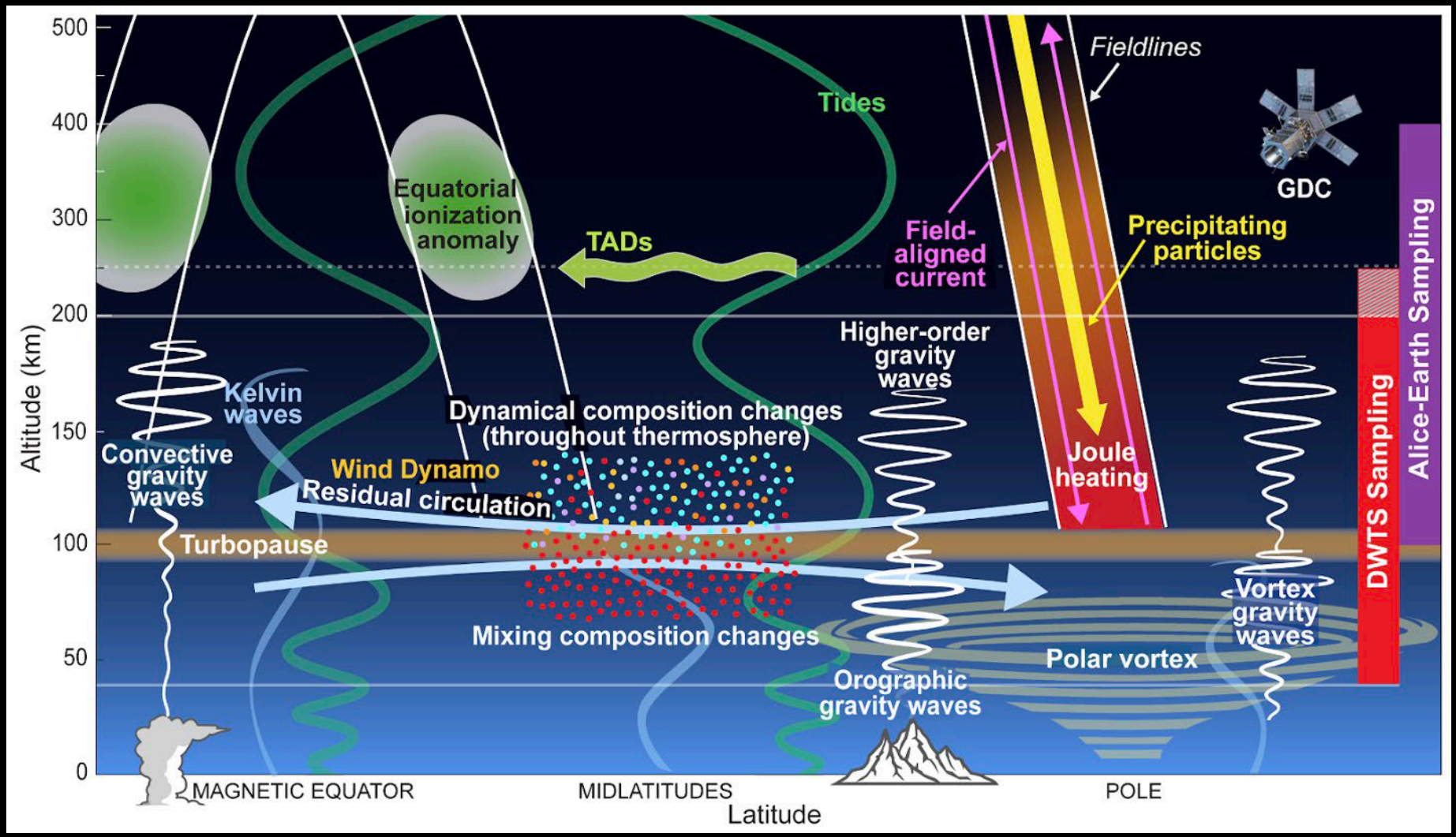
Becker et al. (JGR 2022): TID activity correlated with vortex strength

Strong Vortex



Weak Vortex



- Simulated thermospheric temperature perturbations reduced when vortex is weak
- Observed dTEC variations weaker when vortex is weak

GDC and DYNAMIC are needed to measure global T, U, TADs, and TIDs in the MLT